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COMMUNICATIONS SYSTEMS TECHNOLOGY ASSESSMENT STUDY, VOLUME II RESULTS

by R. L. Kelley, R. K. Khatri, J. D. Kiesling and J. A. Weiss

FAIRCHILD SPACE AND ELECTRONICS COMPANY
GERMANTOWN, MARYLAND

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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16 Abstract

This study examines the cost and technology characteristics for providing special satellite services at UHF, 2.5 GHz, and 14/12 GHz. The services are primarily health, educational, informational and emergency/diaster type services The total cost of each configuration including space segment, earth station, installation, operation and maintenance is optimized to reduce the user's total annual cost and establish the preferred equipment performance parameters Technology expected to be available between now and 1985 is identified and comparisons made between selected alternatives. A key element of the study is a survey of earth station equipment updating past work in the field, providing new insight into technology, and evaluating production and test methods that can reduce costs in large production runs. Various satellite configurations are examined. The cost impact of rain attenuation at Ku-band is evaluated. The factors affecting the ultimate capacity achievable with the available orbital arc and available bandwidth are analyzed. Volume I is an Executive Summary, Volume II provides overview of Results and Volume III contains Appendices giving detailed analyses and data.

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FORWARD

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SECTION I

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

A. OBJECTIVES

The Communications Satellite Technology Assessment Study is an examination of cost and technology characteristics involved in the provision of special satellite services in the UHF, 2.5 GHz and 14/12 GHz frequency band. These services are intended to expand U.S. communication satellite activities which presently emphasize long haul carrier type services (leased lines for various data, TV and audio distribution, and high speed preassigned data) to service more in the public interest. Consequently, emphasis in this study is on services to users in both thinly populated rural areas and urban areas, both lacking access to cost effective flexible communication facilities. These communications services relate to health, educational, and informational services and to expanded emergency and disaster services. These services are either services not now provided by the satellite carriers or are services which are not prevalent in existing carrier systems for one reason or another. Concommitantly various new system configurations and technology are examined with the intention of minimizing potential costs and improving utility and cost effectiveness.

The services are divided into three generic categories: The first category is satellite broadcasting, consisting of TV broadcasting (4.2MHz video baseband) and 6Mbps compressed video, radio broadcasting (8 KHz baseband), TV distribution (or rediffusion) and radio distribution (or rediffusion). All have receive-only earth stations. A second category of services having both receive and transmit capability involve teleconferencing using TV (4.2 MHz baseband), or compressed TV (6Mbps), or combined audio/facsimile and multichannel voice and data for point to point service. Teleconferencing is not limited to commercial application but also has applications in education (interactive educational seminars) and medicine (interactive diagnostic services). The multichannel voice/data service is a thin-route telephone and data service intended for so-called unattended "roof top" installations. A third generic service is a satellite-based land mobile service (e.g., communications between moving vehicles such as cars, trucks, buses and trains and fixed earth stations.) Applications involve emergency, disaster and security services as well as communications with private or public vehicles.

The total service cost of each user configuration including space segment, earth station, installation, operation and maintenance costs is optimized to reduce the user's total annual cost and otherwise to optimize service performance. Technology, expected to be available between now and 1985 is identified for the various user service configurations and comparisons made of selected alternatives. The net result is an implicit statement of

the utility of each service measured by a representative total annual cost each user will have to pay. While costs are minimized based on desired performance, available technology, and optimal system configurations further reductions are also possible through the innovative application of advanced technology. Consequently, the study is a logical extension of the ATS series of experimental satellites and U.S./Canadian-sponsored CTS experimental satellite in which technical feasibility has been demonstrated and useful operational characteristics identified. With the total user cost identified, it is now possible to assess both the value and cost of each service potential users.

A key element of the study consists of a survey of earth station equipment at UHF (620-790 MHz), S-Band (2500 MHz), and Ku-Band (14/12 GHz), updating past work in the field, providing new insight into the available earth station technology through 1985, and evaluating production, including large scale integration, (LSI), and test methods that can reduce costs in large production runs. The latter is a key element in providing low cost services. Various satellite configurations based on six launch vehicles ranging from the Delta 2914 to a Dedicated Shuttle launch are examined with regard to spacecraft and communications configurations in order to minimize service costs, identify optimal satellite characteristics (such as transponder power and the utility of various antenna coverage patterns) and indicate the benefits of the "economy of scale". Satellite costs are based on the assumption of a carrier-owned system in which the total space segment charges depreciate all capital, reco er all expenses and provide a fair return on investment. Thus, these charges should be similar to those actually charged in the future for satellite services. Various system arrangements are examined to reduce cost or optimize performance. For example, comparisons are made between frequency division multiple access, (FDMA) and time division multiple access (TDMA), for a teleconferencing configuration, and between U.S. coverage and time zone coverage satellite antenna beams.

Propagation at Ku-Band is attenuated by heavy rain which affects service availability. This study updates previous work in this area, and predicts attenuation characteristics for various locations within the continental U.S. and selected locations in Alaska and Hawaii. The satellite location chosen to provide Alaska communications reduces earth station antenna elevation on the eastern seaboard with resultant degradation in system availability. Nevertheless high quality, cost effective service is still feasible. particularly if the signal characteristics are well designed.

It turns out that the three frequency bands (UHF, S-Band and Ku-Band) each have their unique properties with regard to each of he ser ices and to the various technical alternatives such as single or multibeam antennas, wideband or narrow band transmission, satellite transponder power, earth station G/T and modulation and multiple access techniques. Some services favor one frequency band, other services another. Much has been previously reported on this issue. This study attempts to evaluate the service requirements in terms of the peculiar or unique characteristics of each frequency band. While cost and performance are important in these evaluations other factors also appear. Regulations limit satellite flux density and antenna sidelobe levels and in some cases, orbital positions. No UHF allocation is presently available so that even if services are attractive, considerable uncertainty concerning ultimate feasibility must be extant pending resolution of regulation matters. In the study, performance is determined independent of the regulation limits, however, where applicable these limits are identified so the reader may evaluate the impact of a regulation on a potential service.

Some of the services do not now exist so that this study cannot be complete without recommendations concerning the utility of each service, the research and technology needed, and general system configuration and user population necessary to achieve favorable cost characteristics. Once these factors are understood potential users can plan their operational systems in order to attain the desirable cost and performance goals. For example TV broadcasting for entertainment purposes (assuming for the moment it is found to be a desirable service) is not practical unless millions of users can be identified and a method found to finance a large and expensive satellite.

This study also includes an examination of the factors affecting the ultimate capacity achievable with the available orbital arc and available bandwidth. Technical characteristics involve satellite and earth station antenna sidelobe characteristics, various signals including single carrier per transponder FDM-FM and FM-TV for both broadcast and distribution, single carrier per transponder PSK and mulitple carriers per transponder. In addition, Ku-Band systems experiencing fading either on the uplink or downlink are evaluated. Various methods are considered to reduce the effect of fading due to precipitation attenuation and these methods are evaluated with regard to impact on orbit utilization.

Finally, to determine potential areas where cost and performance improvements can have a significant impact, various sensitivity analyses are carried out. Both satellite and ground terminal cost and performance are changed nominally $\pm$ 10dB and system costs and optimum configurations are then reevaluated. Areas demonstrating cost sensitivity help identify potential innovations which can improve service and cost effectiveness.

B. BACKGROUND

Extensive evaluations of diverse services and technology are being carried out in the ATS (at UHF, S-Band and C-Band) programs and in the joint U.S./Canadian CTS programs (at Ku-Band). These programs have provided valuable insight and background into non-carrier type services which are of keen interest to many users and user communities. Many demonstrations of one way and two way TV and voice and teleconferencing for interactive exchanges and computer-computer interaction give evidence of great interest in services of this type and the general technical and performance characteristics needed. Previous studies, particularly the Stanford University study (1) dated October 1972, provided much valuable data on earth station equipment and cost characteristics which served as a starting point for similar inquiries in this study. Also a Voice from Space (2) a previous study on radio broadcasting, provided measured data on UHF man-made noise and on the characteristics of UHF transmitters. Previous studies, together with the results of this study, provide a clear picture of technical and cost characteristics so that potential users can evaluate the utility and cost effectiveness of services of interest and express these interests to system planners. Hopefully sufficient knowledge and understanding is now available so that the planners can move forward toward operational systems of the proper characteristics so that the desired services may be economically provided in the public interest.

C. LIMITATIONS

The methods used herein to define service characteristics, (signal-to-noise, bandwidth, availability, etc.), equipment costs, including space segment charges and predictions of technology out of 1985 can only be regarded as approximate and tentative. All costs are in terms of 1976 dollars to remove the uncertainties of inflation. However, earth terminal technology changes and more important, industry production costs depend critically on demands for equipment and to a lesser extent on production technology. The same is true with regard to the space segment. While space segment charges used in the study appear reasonable by current practices and the impact of the shuttle has been taken into account, space charges can vary widely. In fact this study shows a broad range of total system costs depending on separate aggregate traffic supported by the satellite. In short, while every reasonable attempt has been made to develop representative costs and performance and anticipate technological impact, the fact remains that we do not know who will build future earth stations or satellites, and when and under what competitive circumstances and with what political or regulatory limitations. Some uncertainties must be recognized and accepted. We do contend that the cost and performance methods chosen here are mutually consistent and representative on an absolute scale.

1.2 METHODOLOGY

A. FORMULATION

The starting point for this study is a definition of specific user services listed in the foregoing introduction. They consist of:

Two Way Services

- TV (4.2 MHz baseband) Teleconferencing
- Compressed TV (6Mbps) Teleconferencing
- Audio/Facsimile Teleconferencing
- Multiplexed Data and Voice
- Land Mobile Service

One Way Services

- TV broadcasting (4.2 MHz baseband) direct to user
- Radio broadcasting (8 KHz baseband) direct to user
- TV distribution (4.2 MHz baseband) - e.g. rediffusion
- TV distribution (compressed 6Mbps) - e.g. rediffusion
- Radio distribution (15 KHz baseband) - e.g. rediffusion

B. APPROACH

For each of these services a compendium of performance is listed identifying signal format, multiplexing, signal quality (carrier to noise density ratio), bandwidth, bit rate. minimum acceptable faded value, etc., in other words. all of the characteristics that define quality of service. For each service a detailed earth station block diagram is developed which identifies critical earth station equipment such as antenna, receivers, frequency converters, etc. and interface equipment which includes (as needed). MODEMS. CODECS. alarm and monitoring equipment. control equipment, power supplies, environmental control equipment, TV cameras. image projectors, loudspeakers, facsimile transceivers, etc.. in other words, all the equipment the user needs to obtain his particular service. Interface equipment is often a dominant part of the total earth station cost.

Having defined user services, performance characteristics and earth station requirements the next step is to identify earth station equipment costs. For critical components such as antennas, transmitters, and receivers. costs must be ascertained as a function of both production quantity and performance. For these major components, specifications of salient technical characteristics and specific lists of questions are prepared. The questions concern the cost affects of production, production methods, supplier's present volume. industry volume, etc. Both the specification and questionnaire are sent to selected suppliers followed in most cases by a visit in which details are ironed out and supplier's facilities and production and test methods are examined. Compilation of data is performed parametrically For example antenna costs versus antenna diameter (or antenna gain) are plotted with purchase quantity as a parameter. The antenna system consists of all of the components and devices needed to make it work. Small UHF antennas consist only of a reflector, feed. supporting structure and receiver housing. Larger more sophisticated antennas may include tracking, feed deicing. waveguide pressurization. etc. Similarly, receiver system cost versus noise temperature and transmitter cost versus power are compiled. all with quantity "buy" as a parameter. This data is entered into a computer. A computer program, using satellite radiated flux density as a dependent variable and taking into account the propagation path and signal quality required for each service, selects the required antenna gain. receiver noise temperature and transmitter power (if required) such that the earth station and satellite annual costs are minimized.

Interface equipment costs are added to the optimized earth station cost. Interface equipment costs are not dependent on earth station or satellite performance but are dependent on both service requirements and quantity "buy", just like antennas, receivers, etc. Since interface equipment costs are important, accurate cost estimates are necessary. However, the interface equipment, devices and components are so diverse and numerous it is not feasible to prepare specifications and questionnaires for each particular item. Consequently except for a few selected critical components such as video cameras, TDMA, systems, MODEMS. TV data compressors, etc. these costs are ascertained by comparing them to other devices and components of similar construction (not necessarily of similar function) and then taking into account special situations such as incorporation of large scale integration (LSI), and influence of large quantity "buys". Learning curves also are found to be of value in predicting costs of most components.

The space segment represents a significant and sometimes dominant cost. The satellite transponder power density is varied over a substantial range. The satellite is also required to provide a single US coverage beam or four US time zone beams. Sometimes eclipse operation is desired, sometimes north south stationkeeping is not. Three frequencies and six launch vehicles are evaluated. It is not practical or necessary to design and cost each particular version (there are thousands of them). Alternatively, the communications satellite performance and cost are modelled parametrically and the program stored in a computer. In the computation the computer starts by selecting a satellite with a single and consequently high powered (and redundant) transponder. Through the link requirements discussed previously for a specific service, this results in a unique definition of the earth station G/T and EIRP. The computer notes and prints the earth station and space segment annual cost. Then the computer selects two satellite transponders for computation which lowers the transponder power, identifies a new earth station G/T and EIRP, etc. However the satellite cost is now (nominally) half the value it was in the previous step because the specific user is using only one of two available transponders. The computer then selects three transponders, four transponders, etc. until the whole useful range of satellite EIRP is encompassed. This data then serves as an input to the overall system optimization resulting in computer print outs of the minimal cost case thereby identfying the optimum earth station parameters such as antenna diameter, transmitter power, and receiver noise temperature and the satellite transponder power. Parametric evaluation of the space segment in this fashion provides valuable insight into the important satellite characteristics for each service.

In some cases, the satellite characteristics (transponder power, antenna field of view, eclipse and stationkeeping requirements) are similar to existing or planned carrier satellites in which case carrier systems can in principle provide these specific services economically. In other cases, the satellite characteristics differ widely from those of existing or planned carrier satellites indicating that a new approach must be taken to satellite design if the minimum costs are to be achieved. This new approach may be crucial to the successful implementation of the service itself and is discussed in more detail in the following sections.

Ku band propagation with its severe fading in heavy rain poses a special problem. Much research has been performed on the nature of Ku-Band precipitation attenuation in order to characterize Ku band links. While the theory is well understood, acceptable data on local climatology, particularly that part characterized by thunderstorms, is lacking. Consequently theoretical predictions of Ku band attenuation are based on theory and weather bureau average rain fall data. This is shown to be roughly corroborated by ATS and CTS propagation data. Fading effects are minimized by adopting approaches taken and standardized in radio relay practice in which the baseband signal-to-noise is allowed to fade approximately 7 dB from the nominal or "clear sky" value and still be acceptable. The carrier-to-noise ratio, (where applicable) is required to be at threshold at this time.

Finally, the land mobile service is found to differ significantly from the other services. Since it is desired to identify service cost versus number of users, the satellite model must provide a varying service bandwidth. This is accomplished by defining

a range of antenna diameters providing a mosaic of antenna beams covering the Continental U.S. (with spot beams for Hawaii and Alaska). Frequency reuse (and hence more effective bandwidth utilization) is achieved with spot beams. The larger the antennas, the narrower the spots and the more frequency reuse and hence bandwidth. Also as the antenna diameter (and weight) increases the available satellite prime power (and weight) decreases. The land mobile user also has antenna choices ranging from simple "whips" to sophisticated antenna arrays. These satellite and earth terminal characteristics are also examined parametrically to identify the regions of minimum cost

1.3 SUMMARY OF RESULTS

A. GENERAL

This section presents an overview of the study results, highlighting aspects of the study, i.e., costs, technology and system configurations believed to be of interest to the reader. The particular values used to describe general results are a consequence of a detailed data perusal by the authors. Hopefully, a majority of readers will agree with observations; however, sufficient detailed data is presented in the two volumes to enable an interested reader to either confirm them, modify them with a new point of view, or find bases for additional conclusions.

B. SERVICE VIABILITY

The computer search for minimum service costs results in a defined annual minimum cost for each service together with a listing of significant system characteristics Each defined, generic service may have many applications and while it is difficult to value a particular application some discussion of the intrinsic "worth" versus cost of each service is believed appropriate. The reader should recall that each service includes space segment charges, earth station installation, operation and maintenance costs as well as the annualized cost of earth station equipment and interface equipment. Inclusion of the space segment charges in particular has a significant influence on the system parameters

1. Two Way Services

a. Point-to-Point TV (4.2 MHz baseband) at Ku-Band per a typical total network of 100 earth stations time sharing the same satellite transponder, results in a total annual cost of \$51,600 per terminal of which the dominant cost is for the satellite. The earth station consists of a 9.9 meter antenna, a $100^{\circ}K$ (paramp type) receiver and a 25 watt high power amplifier. The earth station includes TV cameras, monitors and video/audio diplexers and modulators. Each user has his own dedicated earth station. Increasing the network to 1000 earth stations has little impact on annual costs. Further, the earth station and satellite parameters remain the same. It is clear that Point-to-Point TV is an expensive service; in fact one of the most expensive in the study. However, commercial teleconferencing, hospital to hospital diagnostics and higher educational seminars may be economically feasible. Use for elementary schools is not attractive because of the high cost. It

should be noted that TV is not well suited to the transmission of graphics data (because of poor resolution) unless the graphics (diagrams, tabulations, texts, photographs) are specially prepared. Satellite requirements are not demanding because of the small number of earth stations assumed per transponder (25), and may be provided by common carrier satellites presently envisioned.

b. Point-to-Point (compressed) TV (6 Mbps) has applications similar to those for the uncompressed 4.2 MHz TV. In this case, the transmission rate and transmission cost is reduced by removing redundancy in video picture elements but at the expense of higher cost in high speed digital processors. The earth station equipment is not normally on the user's premises but is brought to the user on demand by an operating carrier. This results in higher duty factors and fewer users per carrier as compared to the Point-to-Point TV service. The earth station and TV camera studio equipment is assembled on the user premises for each particular prearranged teleconference. If 100 total users and 4 users per carrier are considered, the minimum cost earth station characteristics are similar to the previous case, e.g., a 9.9 meter antenna, $100^{\circ}K$ paramp and a 15 watt transmitter. Satellite transponder power is 2.5 watts and the annual cost is $141K per year per user including operators, setup time and transportation. This breaks down to $395 per user per call which could be attractive for commercial and government teleconferencing, and educational seminars but is too expensive for public school education and probable not suitable for health diagnostics.

Compressed TV resolution is the same as for uncompressed TV. However, the service has been augmented with a high resolution facsimile compatibility. Compressed TV can handle scenes with considerable activity, however camera "zooming" and similar actions may cause temporary picture degradation.

c. Voice/Facsimile Teleconferencing is a low cost teleconferencing system which omits the "presence factor" of the human image. High quality audio is assumed and graphics data transmission is rapidly provided (or interactively provided) with high resolution capable of wall projection. Consequently, this teleconferencing method is suitable for well organized meetings with high data transfer requirements (diagrams, tabulations, text, etc.) A total network of 10,000 earth stations, with 17 earth stations sharing each carrier results in annual costs per terminal of $9.5K or $90 per user per call based on an Atlas Centaur sized satellite and Ku Band operation. Optimized earth station parameters consist of 4.4 meter antenna, $260^{\circ}K$ receiver (transistor type) and a 2 watt transmitter. The satellite transponder power is 75 watts, requiring a special satellite design. However, satellite cost is only 18% of the total annual cost

because this is a narrow bandwidth service based on frequency division multiple access (FDMA). An alternate method was examined for providing this service based on time division multiple access (TDMA). In this case all earth stations operate in the "burst" mode (e.g. time share) at a common, high bit rate. No satellite transponder backoff is required. The resulting earth station parameters consist of a 3.5 meter antenna. 450°K receiver(transistor type) and a 1 watt transmitter. The satellite transponder power is 60 watts. However, the annual cost per terminal more than doubles to $22.5K compared to FDMA, of which 88% is for interface (e.g., TDMA) equipment. The FDMA service cost can be attractive to all potential teleconferencing users including public schools (for interactive educational seminars) provided a "medium" without the human image is acceptable. It is interesting to note that a comparison with the Digital Data Service terrestrial network indicates a break even distance of approximately 40 miles e.g., if two terminals are separated by more than 40 miles it is more economical to use satellites.

d. Multichannel Voice/Data Service is a dedicated (12 equivalent voice channel thin route voice and data) service between two points operating 24 hours a day. In a 100 earth station total network at Ku band, based on a Dedicated Shuttle sized satellite. the optimum earth station parameters are a 7 meter antenna. 265°K receiver (transistor type) and a 2 watt transmitter. The satellite transponder power is only 1.8 watts and can be provided by a carrier type satellite. The annual cost per terminal is $38.8K of which 50% is the satellite charge. Break even distance with the terrestrial Digital Data Service is approximately 60 miles and hence is an attractive satellite service provided the aggregate bit rate can be supported.

e. Land Mobile Radio Service provides UHF communications between mobile terminals such as cars. trucks, buses and trains and fixed Ku band terminals which are connected into the terrestrial dial-up network. For 100.000 total users, 50 sharing each channel frequency and a Dedicated Shuttle sized satellite. the user terminal consists of a simple crossed dipole/folded monopole antenna. a 300°K receiver (transistor type) and a 2 watt transmitter. The U.S. is covered by six contiguous satellite antenna beams with 1.8 kW per beam, e.g., the satellite is large, has a large antenna and high power. The user total annual cost is $1.1K, acceptable for many commercial and governmental applications. This service appears technically and economically attractive and is a service not available in the U.S. except in urban areas.

2. One Way Services

a. TV (4.2 MHz) Distribution can be provided at S-Band or Ku-Band for either distribution of network programming or as an information/distribution service, (for example to universities or to doctors). The annual cost for 500 users is $14.3K per user at Ku-Band and $11.8 K at S band. For 100,000 users the annual cost at Ku band is approximately $2.1K and $1.1 K at S band, however, in this case flux density limits are exceeded. Earth station characteristics at Ku band are 7 meter antenna, 400°K receiver for 500 terminals. and a 3.7 meter antenna and 600°K receiver for 100,000 terminals. Earth station characteristics at S-band are a 3.6 meters antenna, 200°K receiver for 500 terminals and a 2.2 meter antenna, 410°K receiver for 100,000 terminals. Ku band satellite transponder powers for 500 and 100,000 terminals are 15 watts and 78 watts respectively. S-band satellite transponder powers for 500 and 100,000 terminals are 10 watts and 42 watts respectively. The S-Band satellite transponder power for 100,000 terminals exceeds the power flux density limitations.

b. TV (4.2 MHz) Broadcast-direct to the user can be provided at Ku-band, S-band and UHF for entertainment or informational purposes. Service applicability relates to the number of users and to the size of the satellite. Considering the Dedicated Shuttle-sized satellite the following annual costs are computed.

No. of Terminals	Annual Cost ($)		
	Ku Band	S Band	UHF
1,000	5400	3300	1700
10,000,000	155	95	70

Thus, a consumer-type satellite service is definitely feasible from a technical and economic point of view with the UHF the lowest cost. The question of feasibility for this service rests ultimately on finding an application which is complementary to the available and well developed terrestrial broadcast services which provide a diversified (publicly and privately) sponsored program with localized programming capability. One application possibility is as an instructional education TV broadcast service either publically or privately sponsored. This service could be improved by providing one-way TV broadcast capability with a narrowband voice only interactive capability in the reverse direction. However, the latter was not considered in this study. Even a network of 1000 terminals appears economically attractive for university, professional or trade group education. The satellite transponder power at Ku band is approximately 10 watts and 1050 watts for 1000 and 10,000,000 terminals respectively. Satellite transponder power (4 beam satellite) at S band is approximately 10 watts and 1050 watts for 1000 and 10,000,000 terminals respectively with 20 watts at the flux density limits. Satellite transponder power (4 beam satellite) at UHF is approximately 10 watts and 1400 watts for 1000

and 10.000.000 terminals respectively. Earth terminal optimum antenna diameters for 10,000,000 terminals are less than 2.5 meters at Ku-band, and less than 0.7 meters at S band and UHF. Over the range from 1000 to 10,000,000 terminals transistor-type receivers are generally favored.

c. TV (6 Mbps) Distribution in a compressed TV format for educational and informational services can be supplied at Ku band and S band. Considering an Atlas Centaur sized satellite the following annual costs are computed:

No. of Terminals	Annual Cost (S)	
	Ku-Band	S-Band
100	21,500	21,500
10,000	7,000	6,700

Satellite transponder powers are less than 20 watts at both Ku band and S band. Over the range from 100 to 10.000 terminals the Ku band antenna diameter decreases from 4.5 meters to 2 meters and at S band from 2.5 meters to 1.8 meters. Over this same range transistor type receivers are the optimum choice.

d. Radio (15kHz) Distribution providing all forms of audio programming for music and voice can be provided at Ku band and S band. Service applicability relates to the number of users and to the size of the satellite. Considering an Atlas Centaur sized satellite the following annual costs are computed:

No. of Terminals	Annual Cost (S)	
	Ku-Band (4 beam)	S-Band (4 beam)
100	4,700	2,900
10,000	1,400	900

Ku-band satellite transponder powers are approximately 20 watts and 120 watts for 100 and 10 000 terminals respectively. S band satellite transponder powers are approximately 25 watts and 125 watts for 100 and 10,000 terminals respectively Over the range from 100 to 10,000 terminals Ku band earth station antenna diameters range from 4 meters to 2 meters and at S-Band from under 2.5 meters to over 1.5 meters. Over this same range the Ku-Band and S-Band receivers change from transistor types to diode mixer types.

e. Radio (8 kHz) Broadcasting direct to the user can provide entertainment, educational or instructional service at Ku-Band, S-Band and UHF. Considering an Atlas Centaur sized satellite, the following annual costs are computed:

No. of Terminals	Annual Cost ($)		
	Ku-Band	S-Band	UHF
10,000	630	365	260
10,000,000	210	100	80

For the range of terminals from 10,000 to 1,000,000 Ku band satellite power varies from approximately 70 watts to over 180 watts, at S band from approximately 100 watts to 350 watts, and at UHF from approximately 30 watts to 550 watts. Over this same range antenna diameters range between 1 to 2 meters at Ku band and between .6 to .3 meters at S band and UHF, and all receivers use diode mixers. For large number of terminals, say a million or more, satellite costs (and hence transmission costs) are inconsequental. The most dominant tradeoff in this region is the effect of quantity buying.

C. COMPARISON OF FREQUENCIES FOR BROADCAST SERVICES

For similar services with satellite antenna beams constrained to illuminate similar areas, a direct measure of earth station performance is its aperture area divided by system noise temperature. For the same aperture area, lower frequency antennas cost less because of relaxed mechanical and electrical tolerance. In addition, lower frequency antennas may not require tracking, de-icing, or waveguide pressurization while their higher frequency counterparts may. In addition, lower frequency receivers can achieve lower noise temperatures for the same cost, and do not require precipitation margins. Even for the land mobile service, simple antennas like whips and folded monopoles have relatively large apertures. consequently lower frequencies result in lower earth station costs. There were no exceptions to this rule in the study. On the other hand, the lower frequency satellites are penalized substantially by the larger satellite antennas necessary to illumi-

nate the coverage area. This low frequency problem is accentuated as the satellite antenna beam is narrowed and is only partially compensated by added propagation margins and transmission line losses incurred by the Ku-Band Satellites. Finally, for this study, multi-frequency multi-service satellites are assumed, in order to explore the economy of scale offered by larger "multipurpose" satellites. Satellite size therefore is not constrained by the allocated bandwidth of a single frequency band or single service. Under these circumstances, the services at lower frequencies are lower in cost almost without exception. However, the differences in system annual costs due to use of different frequency bands while significant, is not as significant as the economy of scale achieved through large numbers of users per service.

D. IMPACT OF REGULATIONS

Operation in S-Band is subject to the flux density limitation of $(-152 + \theta/15)$ dbw/4KHz/M^2 where θ is the earth station elevation angle in degrees. Observance of this restricts satellite power particularly for services like broadcasting which involve large populations (the minimum cost parameters involve large satellite transponder powers). If the satellite power is fixed at the regulatory limit, service costs will increase. In most cases where this impact was evaluated, the increased service cost at S-Band remained below those of the corresponding Ku-Band system. Further, terminal antenna diameters remained, in general, less than those required at Ku-Band. There are essentially no flux density limits at Ku-Band, only requirements to coordinate with owners of adjacent satellites if satellite separations are less than prescribed. Additionally, broadcast satellites should be designed to provide peak powers below 63 dBw in order to comply with constraints on overlapping radiation at the edge of national boundries. There are no restrictions placed on UHF satellite services because these services are not permitted by existing regulations.

E. EARTH STATION PARAMETERS

The optimization process which achieves a minimum system cost is not particularly sensitive with regard to earth station (or satellite) parameters. Typically a 2:1 variation in a performance parameter such as an antenna or receiver (or satellite power) results in a 10 to 20 percent change in system cost. Transmitter power and cost, while important factors in the earth terminal optimization, are not major factors in the overall system optimization. In general, low-cost transistor type or diode mixer type receivers are the optimum choices for most services over most of the range in earth terminal numbers of interest. However, optimum Ku-Band antenna diameters selected tended to be larger than those in current usage. One reason for this, of course, is consideration of satellite charges (for operational systems) as contrasted to the present experimental demonstrations for which there are no satellite charges. A second reason is the 10-year antenna depreciation assumed in the cost annualizing factor which reduces the "impact" of the larger antennas to the user. For example, if a 3-year depreciation schedule had been assumed instead, the optimum antenna size would have been reduced.

Interface equipment is often a dominant cost in the earth station. For those items which are basically digital in nature, substantial reductions in cost can be achieved by the use of large scaled integration (LSI) particularly the new I^2L (ion injected logic) technology. LSI is having a revolutionary effect on the cost and performance of digital equipment.

Unfortunately most of the earth station subsystems are not composed of digital logic. Except for LSI and the new GaAs FET low noise receivers, earth station technology is relatively mature.

F. SATELLITE PARAMETERS

The range of antenna sizes and transponder powers required for good service performance and economy are within present experience if the NASA experimental satellite experience is included. UHF antennas are large, particularly for time zone coverage. TWT efficiency at S-Band and Ku-Band is high and comparable. Since earth station HPA power is not a sensitive item, the satellite G/T also is not critical. Existing technology with the exception of that required for the Land Mobile Satellite is sufficient to achieve good performance and cost. However, significant improvements in cost and performance can be achieved with certain spacecraft improvements, for example, ion engines and fuel cells, but there are no plans to conduct the necessary in-orbit demonstrations. Use of Shuttle has a significant and favorable impact on system costs because of the lower launch costs and the higher reliability (which reduces launch insurance costs). In addition, the Shuttle short turn-around time in emergency situations may encourage satellite operators to keep spare satellites on the ground; this can decrease operating costs. Finally, a substantial economy of scale is predicted for larger, multipurposes, multiservice, multifrequency band satellites. In general, high frequency satellites with time zone antennas instead of U. S. coverage antennas result in lower system costs. However, at lower frequencies, there is no substantial difference in operating costs due to different satellite antenna coverage areas. Further, in many non-mobile narrow band service cases there is no substantial cost difference at any frequency. Consequently, the use of multiple spot beams to reduce costs may be restricted to the wideband services. Note, however, that use of multiple beams may be important for increasing bandwidth through frequency reuse.

G. PROPAGATION

Ku-Band propagation is difficult to characterize for each location in the U. S. because experimental data still is lacking (CTS data is not yet available). Satellite designs considered in this study focused more energy toward the Gulf of Mexico--Florida area (where substantial attenuation is experienced because of precipitation) than elsewhere in order to achieve a more uniform "outage" characteristics across the U. S. Excess costs due to precipitation attenuation (by the cost of added "link" margin) are insignificant for outages as low as 0.2% but costs increase rapidly for lower outages. For outages of .01%, the services to the Gulf of Mexico--Florida region are not economical for single antenna earth stations with fixed margins; more complex satellites and earth stations configurations are needed. Satellite location is an important consideration for Ku-Band systems because of the added path length through thunderstorms encountered at low elevation angles. For this study, a satellite longitude of 124° W is chosen in order to provide service to Alaska. This substantially reduces earth station elevation angles on the eastern seaboard further exacerbating the precipitation attenuation problem. Propagation at S-Band is nearly ideal. At UHF, however, circularly polarized antennas are needed to overcome the effects of Faraday rotation. Propagation through trees, buildings and other structures, and multipath from nearby water and land can be troublesome to mobile terminals having low gain antennas. Manmade noise, characteristics of large cities and caused primarily by automobile ignition systems is signifi-

cant (as is "showing" by large buildings), so that a land mobile UHF, satellite service for cities will be expensive or have poor performance or both. Suburban and rural areas are better suited for a satellite mobile service.

H. ECONOMY OF SCALE

Most services achieve practical costs only if sufficient numbers of earth stations can be procured. Earth stations and related equipment all cost substantially less if purchased in large enough quantities. Satellite costs are borne by all the users supporting that satellite or fraction thereof. Finally, the optimum earth station and satellite performance are critically dependent on the size of the earth station network and, of course, on the nature of the service (e.g. bandwidth, modulation, etc.) What results is a "chicken and egg" issue relating to how the system costs are to be supported as the network grows, perhaps over many years, to its final, optimum configuration. Compounding this problem are the uncertainties with regard to the user community as a viable market, the limited resources per user (the aggregate resources, however, can be enormous), and the problems of billing the users and marketing user services. These problems suggest that some form of government-sponsored or supported program may be necessary during the "infant" years of service in which properly designed satellite services can be made available and earth station equipment, meeting proper specifications and perhaps produced in limited quantities to achieve lower prices also can be made available.

I. ORBITAL CAPACITY

The orbital capacity is dependent on the satellite and earth station antenna sidelobe characteristics, modulation parameters, access techniques, the earth station aperture diameter, frequency, satellite spacing, the mix of services experienceing mutual interference, uplink and downlink fading characteristics, and many other parameters. It is apparent that improvements in antenna sidelobe characteristics can have significant benefits. In the case of Ku-band link fading, link power control and antenna diversity can be effectively used to increase orbital capacity. Ku-Band link fading is due to rain attenuation resulting in reduced signal level relative to interference and thermal noise and increased receive system thermal noise level. Application of interference rejection techniques such as multibeam satellite antennas, spread spectrum modulation, active interference cancellation, dual polarization, etc. can also increase orbital capacity. In the absence of any fading compensation or interference rejection techniques, Ku-Band satellite spacings as low as 1^{o} to 2^{o} appear acceptable for either broadcast or fixed services, if these services are isolated to different parts of the orbit (as was agreed at the 1977 WARC). Consequently, the orbital capacity for telecommunications at Ku-Band is substantially larger than at C-Band. S-Band satellite spacings of $2\text{-}3^{o}$ also appear feasible.

1.4 OBSERVATIONS

A. The generic services considered herein, e.g., TV and radio broadcasting, TV and radio distribution, teleconferencing, thin route voice and data, and land mobile are attractive satellite communication services with regard to cost and application. Some of these, namely TV and radio distribution and thin route voice and data are already provided by existing satellite and terrestrial carriers for commercial applications. However, many attractive applications also exist which are not being provided by existing carriers, because the satellite characteristics are not optimum and result therefore in excessive system costs (e.g. large satellite powers are needed for broadcasting) or the correct frequency band is not available or the low cost earth station equipment is not available (in production quantities), or the user market is not developed or is uncertain - or a combination of these.

B. Economy of scale is the most dominant cost controlling mechanism. This relates particularly to the earth station network size.

C. Operating frequency band, while important (in general the lower the frequency the lower the cost) is not significant compared to the economics realized from achieving the proper earth station population and a properly sized space segment.

D. Flux density limitations limit satellite power of some services (S-Band broadcasting) to lower-than-optimum values. These limitations increase system costs but for reasonable sized systems (e.g. (10^6 receive only stations) do not increase them substantially. At the flux density limit, the satellite power density and earth station G/T are fixed. As the network grows from this point, the satellite costs are still being prorated over a broader community, thus reducing the satellite cost per user. The user is also obtaining lower cost terminals because of larger production "buys." For example, increasing the earth station network size by an order of magnitude past the point at which satellite flux density is limited reduces the space segment user cost by a factor of 10. If learning curves apply, the earth station cost, by virtue of larger "buys" also is reduced by approximately 30%, so that considerable economies still apply. If the satellite power could be increased past the flux density limit so that earth station G/T also could be reduced, further savings of approximately 10-20% result.

E. Proven satellite and earth station technology is available for the low risk implementation of all the generic services except for the Land Mobile Service. The latter requires R&D for:

- Low cost, mulitple channel mobile transceivers.
- Lightweight satellite transponder development
- Mobile antenna development and test under operational conditions
- Large aperture, multiple beam, deployable satellite antennas
- Linearized UHF satellite transmitters

F. Precipitation attenuation at Ku-Band does not have a serious impact on cost unless outages of less than 0.2% are envisioned. A satellite location chosen to accomplish satellite service to Alaska has a significant impact on Ku-Band precipitation characteristics for the northeast. City ignition noise multipath fading and building shadowing limits the effectiveness of the UHF Land Mobile Service in urban areas. Even in suburban or rural areas shadowing (by trees etc.) and multipath still may be major problems.

G. Orbit capacity is affected by antenna sidelobes, the ability to make use of orthogonal polarization to permit frequency reuse, and the earth station aperture size. Modulation parameters, signal bandwidth, fading due to precipitation attenuation, have lesser impact. Mixtures of earth stations with different antenna sizes, e.g. intermixed broadcast and fixed service satellites also may have an important impact on orbit capacity. However, this issue was not evaluated in the study. It appears that satellite spacing at Ku-Band can be as little as 1°, and as little as 2-3° at S-Band. Much additional R&D, particularly with small antennas to improve sidelobe and polarization, can greatly enhance the orbit utilization.

H. While significant, industry-sponsored R&D is performed in satellite communications components such as antennas, TWTs, lightweight transponder filters, and low noise (GaAs FET) receivers little additional progress is being accomplished on components requiring orbital test flights, such as ion engines, fuel cells, magnetic bearings, ultra lightweight solar cells for synchronous orbit and more complicated access systems such as satellite switched TDMA (SS-TDMA). Development of these components to operational readiness can reduce space system costs and ought to be accomplished by on-going experiments in communication satellite programs. The UHF land mobile satellite is such a radical departure from the state-of-the-art that its development can only be accomplished by a major R&D ground and flight test program. An example of the impact of R&D on reducing communications satellite system costs is described herein with regard to the Shuttle development.

I. The dominant earth station performance parameter is the so-called figure of merit G/T. This, in conjunction with the satellite EIRP and cost form the dominant tradeoffs. It is found that for services requiring uplinks, the optimum arrangement of G/T and EIRP is normally near the value determined if only the downlink is considered. That is, while the transmitter costs can be high, transmitter performance has only a small impact on optimum earth station G/T.

1.5 REPORT ORGANIZATION

This report has been divided into three volumes in order to assist the reader in his task of assimilation. Volume 1 is an executive summary giving major study objectives, conclusions, and implications to the future of special user satellite communications services. Volume 2 contains the essence of this study with the analytical and computational aspects omitted except for brief summaries. Readers interested in essential characteristics--cost, performance, and general characteristics - can obtain these from Volume 2. Detailed Analyses and data tabulations are confined to Volume 3, where they may be consulted if desired.

Volume 2. Section 2, defines the generic services and lists the service performance characteristics, and general system considerations. An earth station block diagram is defined for each service. In addition, each generic service has examples of potential applications to aid the reader in identifying service possibilities. Section 3 describes the tradeoffs for the receive/transmit services leading to a definition of service costs and the optimum earth station and satellite characteristics for each particular service. The earth station model (G/T and EIRP vs. cost) and satellite model (transponder power vs. cost) are briefly described. Section 4 describes similar tradeoffs for the receive only services, again leading to a definition of service cost and the optimum earth station and satellite characteristics for each service. Section 5 describes factors influencing the orbital capacity considering both broadcast and so-called fixed services. Section 6 describes significant technology for earth stations, satellites and the overall system (through 1985) which appear to have a high impact on service costs and performance.

Volume 3, Appendix 1, contains the details of the earth station equipment survey leading to the formulation of the earth station G/T and EIRP vs. cost, with production "buy" as a parameter. Earth station technology and technology trends and the methods used for conducting the supplier surveys also are discussed. A list of contacted suppliers is given. Appendix 2 develops the satellite models for the three frequency bands and six launch vehicles leading to the formulation of the transponder cost versus power, with six launch vehicles as parameters. Appendix 3 summarizes the research into Ku-band progagation and gives the detailed Ku-band outage characteristics vs. margins used in the tradeoffs for the different areas of the country. References also are listed. Appendices 4 and 5 present the complete results of the transmit/receive service tradeoff evaluations and certain detailed analyses better treated separately. The tradeoff results are provided in graphical and tabular form. Appendix 6 lists the detailed methodology for the orbit capacity computation. Appendix 7 presents the complete results of the broadcast service tradeoff evaluations. The results are again in graphical and tabular form.

The capabilities of the fixed , broadcasting, and land mobile services are discussed in the following paragraphs.

2.2 CAPABILITIES OF THE FIXED SERVICES

A. INTERACTIVE TV TELECONFERENCING

Interactive Point-to-Point TV service has the capability to improve the quality and availability of educational and health care services to all sections of the population, and provide effective means for information exchange. In the past few decades it has become apparent that medical training requires up-to-date course material and information in order to acquaint both the practitioner and the student with the rapidly expanding body of scientific knowledge. Interactive Point-to-Point TV service can fulfill this demand in an economical and efficient way. The vital role that interactive Point-to-Point TV service provides in extending educational and medical services to the thinly settled non-urban areas has been demonstrated by the ATS-6 experiments in Alaska, the Rocky Mountain states and Appalachia.

The evolving medical and professional courses, adult education programs, open university classes, and corporate training programs are all evidence of a trend requiring non-traditional (outside the classical classroom setting) type of programs. This trend is caused by

- Escalating energy and travel costs.
- The increasing cost of new traditional educational facitilies.
- The demands of work or household duties being such that many students can afford to study only at their own pace and convenience.
- The fact that many students cannot afford the cost of conventional education.
- Many geographical areas being so remote from the traditional learning centers that the student finds it extremely difficult to reach the nearest learning facility.

The feasibility of higher education and information exchange (on a nationwide basis) is presently being demonstrated by the various CTS experiments. For example. the CTS digital Video Curriculum Sharing experiment is designed to demonstrate the remote classroom principle by classes conducted between Stanford University (in Stanford USA) and Carlton University (Ottawa, Canada).

The emergence of organizations like the Public Service Satellite Consortium (PSSC), or the Public Interest Satellite Association demonstrate a growing general national commitment to improvements in health and education.

SECTION 2

SERVICE DEFINITION

2.1 INTRODUCTION

The purpose of this section is to identify the generic services evaluated in this study, define service operating characteristics, indicate examples of applications, provide system block diagrams, and summarize service performance characteristics. Each service requires characteristic interface equipment, e.g. the equipment between the earth station IF and the user. The cost of this equipment is significant. It is added to the basic earth station and space segment cost to obtain the total annual cost of the service. Service characteristics in terms of equipment redundancy, test equipment and miscellaneous items such as alarm and control equipment can also affect the earth station cost. The basic services are defined as:

Audio Teleconferencing (interactive)

TV and Radio Distribution (for retransmission)

Video Teleconferencing (interactive)

TV and Radio Broadcasting, (direct to user)

Multiplexed Data and Voice (point to point)

Land Mobile

These services may be regarded as generic services: First each consists of a basic capability for which many user applications may be found, for example TV and radio distribution may be for commercial or private networks or for educational, instructional or medical purposes. Second, some of these generic services can be subdivided into other service categories; for example, TV may be broken into 4.2 MHz video and compressed video.

An important objective of this study, therefore, is to determine the cost and technology of each of the generic services in order to provide a measure of utility or worth. It is hoped that these analyses will prove of value in evaluating various methods by which the most cost effective and useful services may be developed into operational services for the public benefit.

It should be noted that in defining the services and service characteristic emphasis is placed on quality characteristics which favor educational, instructional, medical and entertainment type applications and not the existing common carrier services. Of course, it may turn out that some of these services will be provided by the existing carrier services. Others will not be economic unless new satellite facilities with different technical characteristics are created.

B. INTERACTIVE COMPRESSED TV, TELECONFERENCING

One of the most important applications of this service is teleconferencing. A conference in general can be defined as: a meeting of two or more persons who interactively participate in an exchange of ideas and express their opinions on subjects that are of common interest. When face-to-face communications or instantaneous picture transmission of two dimensional moving objects is required, (e.g. patient monitoring or medical diagnosis) then the teleconferencing process must involve both video and audio communications.

Teleconferencing has the advantage of reducing the costs involved in business travelling. Normally, a two to three day trip is required coast to coast for a one or two hour conference. Another advantage is employee participation. For example, an entire project team cannot attend a conference that includes three days travel for each project team member. With a teleconferencing capability, all of the involved personnel can actively participate.

If a video conferencing service requires only a limited amount of time per week, then the same service channel can also be used for company (or organizational) training, for transmission of data. for remote job entry terminals (for computer applications), or simply for voice or facsimile services. Alternatively, many users may share the same channel, gaining access to it on an "on demand" basis: and in this case, the users will share the space segment charges. This service potentially provides economical alternatives to some of the interactive full bandwidth TV services. Some examples of these services are:

- Education (for example curriculum sharing)
- Law enforcement activities
- Patient monitoring

C. INTERACTIVE VOICE/FACSIMILE TELECONFERENCING

This service can provide an economical and effective means for teleconferencing. It can supply a rapid facsimile service along with voice or data traffic. The facsimile service permits the rapid (several seconds) transmission of graphics data, such as "vugraph" material, photographs, contract wording, business plans, lecture notes, etc. in a secure form (if needed) and can provide wall projection with excellent resolution.

If the teleconferencing service requires only a limited amount of time per week, then the same channel can be used for other purposes such as voice or facsimile traffic, or it can be used by other users.

D. INTERACTIVE MULTI-CHANNEL VOICE/DATA

This service is applicable to library exchange, consumer services. business data, electronic mail, and telephone. This service is presently emphasized in the

satellite carriers and the service is available commercially. An objective in this study is to examine the service for applicability to noncommercial purposes, for example, computer and library data exchange between universities or hospitals.

2.3 BROADCAST SERVICE CAPABILITIES

A. TV DISTRIBUTION FOR LOCAL RETRANSMISSION

This service is of interest to both the private and public segment of the country. The Public Broadcasting Service (PBS) has recently acquired three video channels from the Western Union Satellite service to broadcast video services to some 160 earth stations. It is expected that the needs of PBS (and of government agencies both in the federal and the local levels for similar applications) will increase at least by an order of magnitude in the decade starting with 1980.

The private broadcasting networks such as, ABC, CBS and NBC need a real-time nationwide sports broadcasting network, that includes programming from any point to any point/points in the nation. A nationwide on-the-spot emergency or disaster broadcasting service presently depends on the broadcasters' ingenuity; and often this type of coverage is lacking. Due to financial limitations, many points in the nation are not covered by the three major networks.

Thus, it can be seen that both private and public broadcasting companies can greatly benefit from a media that provides easy and economical nationwide TV broadcasting coverage.

B. BROADCAST TV DIRECT TO USER

TV broadcasting instead of TV distribution with retransmission can be attractive in thinly settled areas of the country. In this case, it can be regarded as an alternative to conventional broadcasting or a complement to it. In addition to its national entertainment function broadcast TV may be used for:

- Thinly settled areas not accessible to conventional broadcasting service.
- The dissemination of Governmental information
- Communication services for law enforcement purposes
- Educational services (this case is similar to an educational service using TV and voice or voice and fax one way and voice the other way for interactive applications).
- Weather and emergency information services.

C. FM VOICE/MUSIC DISTRIBUTION FOR LOCAL RETRANSMISSION

FM Voice /Music Distribution for local retransmission can provide several categories of services, for example:

- Music service for commercial use (hotels, motels, factories, etc.)
- Music for the general population (commercial networking)
- Federal and local governmental use for
  - emergency and warning information
  - law enforcement information
  - information distribution

D. BROADCAST COMPRESSED TV DIRECT TO USER

This service is similar to TV (4.2 MHz) broadcast direct to user, however, it requires additional hardware expenditure to provide the desired compression level along with the required broadcasting quality. It can be used to disseminate local emergency, weather and agricultural information. It can also provide a broadcasting capability for local educational and health care facilities. Local governments and public services can use it for employment services, consumer information and family planning.

E. BROADCAST VOICE /MUSIC DIRECT TO USER

This service can complement broadcast facilities and can provide entertainment, information and education services direct to the user.

2.4 LAND MOBILE SERVICE CAPABILITIES

The land mobile satellite service can provide communication services between a moving terminal such as a truck, train, plane, bus or car, and a fixed terminal which connects the call into the telephone network. Example of uses are:

- Emergency communications for ambulances, police, fire, rescue vehicles and security forces.
- Communication services to trucking and railroad industries in their efforts to optimize their routing.
- Communications between travelling personnel and headquarters to coordinate routes and provide information while in transit, (e.g. a salesman).

- Communication services to various transportation industries (for example taxis, busing and inner city train services).

- Communication services to private organizations in their marketing and sales efforts for accessing customer files, and pricing and inventory information.

- Communication services to all public and government employees while enroute in thinly settled non-urban areas.

2.5 FIXED SERVICES CONFIGURATION/CHARACTERISTICS

A. INTERACTIVE TV, TELECONFERENCING

This system is configured to occupy a single satellite transponder; however, the transponder can be time-shared with other users and made available on an "on-demand" basis. A TV camera system with appropriate user interface system is provided with this configuration. The configuration is based on a studio operation since the operating mode is primarily teleconferencing. Earth stations for this service are unattended, non-redundant receive/transmit earth stations; and they access the satellite on a demand assigned basis. Figure 2-1 is a typical block diagram of the interactive point-to-point TV earth station. In some applications, a switching system could route a number of microphones into a common audio system.

Normally, both the video receive and transmit capabilities are desirable. However, there are a number of applications where only video receive with audio talk-back capability is desired. For example, in our educational or instructional application, only the instructor is required to be televised. The students (or the audience) needs can be satisfied by a talk-back capability. Thus, the complexity of this earth station is governed by the selection of specific user types and their particular communication needs.

Signal Characteristics

The TV picture is generated by a 525-line TV signal whose frame rate is 30 frames/sec. Modulation characteristics for this service are derived in Appendix 5.1 and are summarized in Table 5-1. These characteristics are:

a. Maximum audio frequency; fm = 15 KHz

b. Maximum video frequency; F = 4.2 MHz

c. Audio subcarrier frequency; fsc = 6.5 MHz

d. Threshold video carrier-to-noise-ratio

$$\left[\left(\frac{C}{N}\right)_v\right]_{Threshold} = 12 \text{ dB}$$

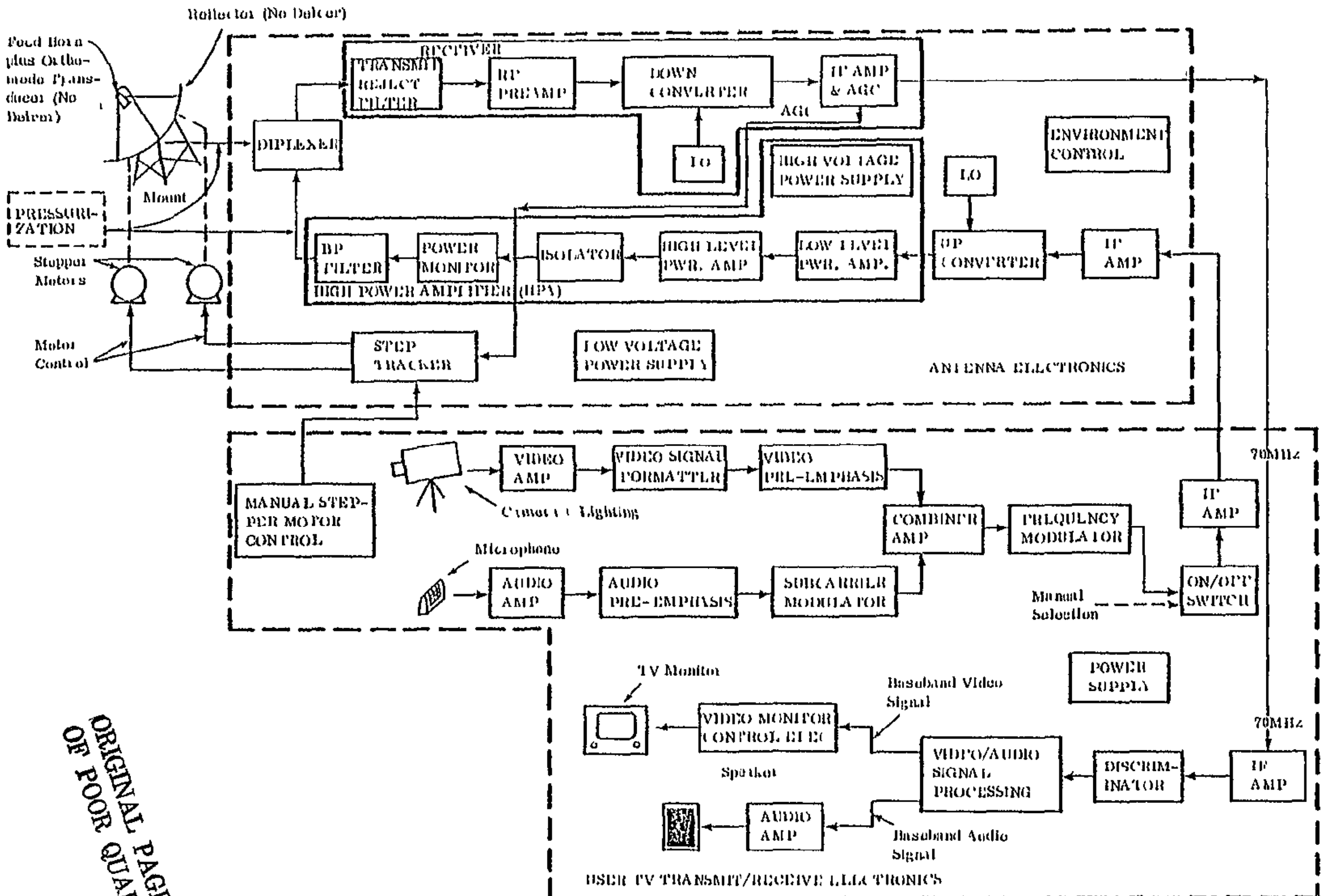

Figure 2-1 Transmit/Receive Terminal (Interactive Point-to-Point TV)

e. Threshold audio carrier-to-noise ratio

$$\left[\left(\frac{C}{N}\right)\right]_a \text{ Threshold} = 12 \text{ dB}$$

f. Audio subcarrier bandwidth, $B_{sc} = 245$ KHz

g. TV signal predetection bandwidth, $B_n = 22$ MHz

h. The video peak-to-peak signal-to-rms weighted noise ratio, Spp/Nw = 40.16 dB which is a minimum requirement. With a 7 dB carrier-to-noise ratio margin the Spp/Nw is between 40.17 dB and 47.17 dB.

i. The audio test-tone signal to weighted noise ratio, S/N, = 43dB. This S/N is a minimum performance criteria, and with a 7dB margin the S/N is between 43dB and 50dB.

j. Peak carrier deviation due to the video signal, ΔFp, = 4.8 MHz

k. Peak carrier deviation due to the audio signal, Δfc, = 1.1 MHz

l. Audio modulation index, Mz = 7.166

B. INTERACTIVE COMPRESSED TV

In this configuration, multiple TV signals per transponder are time shared by the users in an FDMA system. Each link is assumed to have a full duplex TV receive and transmit capability. The earth stations of the interactive compressed TV service are non-redundant receive/transmit earth stations and access the satellite channel on a demand assigned basis. Transportable stations are provided allowing users to pay for the total service on a per call basis. Service personnel erect the stations and operate the video equipment during conferences. Figure 2-2 is a typical block diagram of the interactive compressed TV earth station. The RF, IF and user interface equipments are the same as in the full bandwidth TV service, except for the digital compression/expansion which is accomplished by the NTSC/TDM (or TDM/NTSC) converter and the interframe codec (coder/decoder). At the transmission end the picture camera is directly connected via the NTSC video amplifier to the NTSC/TDM converter, which converts the incoming NTSC color television signal (which has a 4.2 MHz baseband bandwidth) into a TDM (Time Division Multiplexed) signal composed of a time compressed chrominance signal and luminance signal. Subsequently, the TDM signal is encoded by an interframe coder at the rate of 6.3 Mbps. The interframe coding works on the basis of frame-to-frame differential coding and conditional replenishment principles. The frame rate is 30 frames/second. The interframe coder uses a 0.176 Mbps bit rate per frame. Thus, changed elements are delivered with a 5.28 Mbps bit rate. A bit rate of 0.5 Mbps is used for the fixed background transmission and 0.52 Mbps for an error correcting code with a rate 11/12 coding. Thus, the transmission rate is (5.28 + 0.5 + 0.52) Mbps = 6.3 Mbps. During reception the reverse of the above processing takes place.

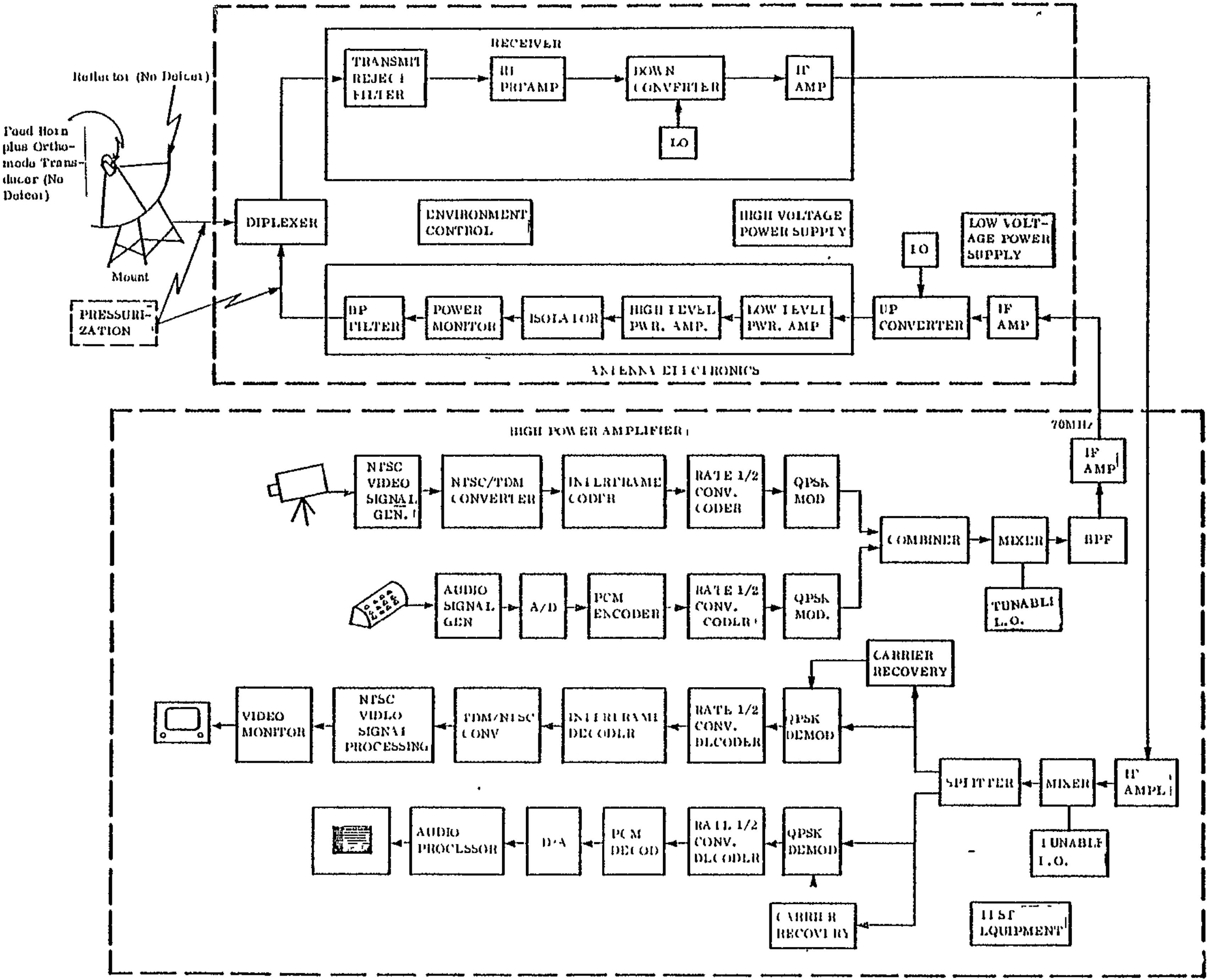

Figure 2-2 - Interactive Compressed TV

It has been observed that for scenes where general motion seldom occurs, (e.g. camera zooming and panning) a 6.3 Mbps interframe encoded video signal gives an acceptable picture quality[3]. Thus, this system is readily (and economically) adaptable to most informational, educational, and instructional, conferencing applications. It is appropriate to note that in the instructional and educational applications a number of microphones may be used.

Signal Characteristics

The TV picture is generated by a 525 line TV signal whose frame rate is 30 frames/sec. Modulation characteristics for this service are derived in Appendix 5.1 and are shown in Table 5-1. These characteristics are:

a. The video interframe encoded bit rate is 6.3 Mbps.

b. The interframe encoded video baseband is rate 1/2 convolutionally coded; and the resulting bit rate is 12.6 Mbps.

c. The digital video baseband is QPSK modulated onto a video subcarrier. The modulated video carrier bandwidth is 7.56 MHz.

d. The audio signal is 64 Kbps PCM.

e. The PCM audio signal is rate 1/2 convolutional coded, and has a coded bit rate of 128 Kbps.

f. The audio digital baseband is QPSK modulated onto an audio subcarrier. The modulated audio subcarrier noise bandwidth is 74.4 KHz.

g. A 12 MHz TV channel bandwidth is allocated for the combined audio and video signals.

h. The minimum performance objective is a BER of 10^{-4}, C/N = 9.1 db.

i. With a 4 dB C/N margin the BER will be about 10^{-7} for 99% or more of the time.

C. INTERACTIVE/FACSIMILE TELECONFERENCING

In this configuration a multiple carrier satellite transponder is time shared by the users in a FDMA system. Each link is assumed to have a full duplex voice/facsimile or data receive/transmit capability. The earth stations of the interactive voice/facsimile teleconferencing service are unattended non-redundant receive/transmit earth stations and they access the satellite on a demand assigned basis. Figure 2-3 is a typical block diagram of the interactive voice/facsimile teleconferencing earth station.

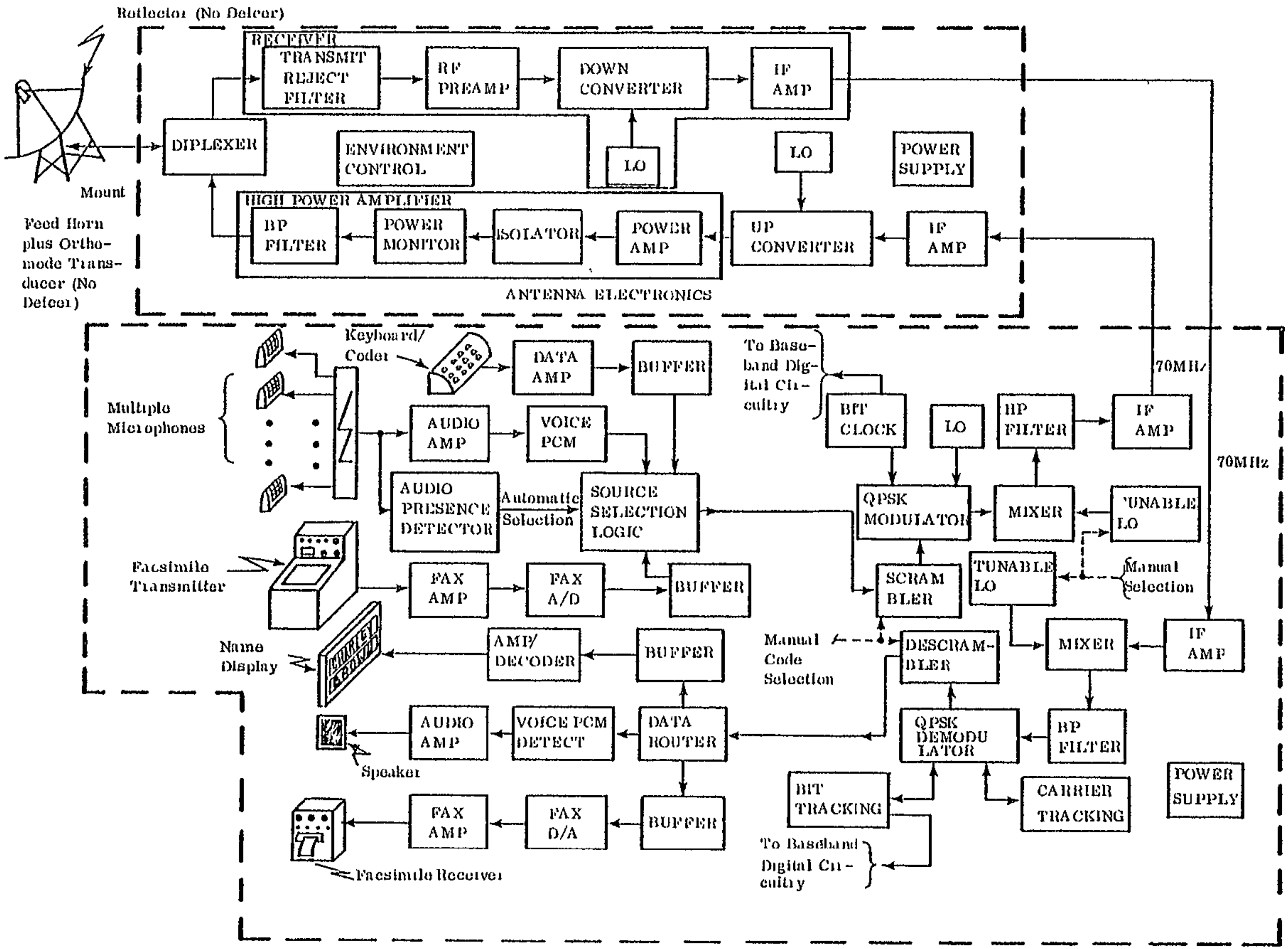

Figure 2-3 . Interactive Audio/Facsimile Teleconferencing

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Signal Characteristics

Modulation parameters for this service are derived in Appendix 5.1, and are as follows:

a. The information bit rate for the voice, data and facsimile services is 128 Kbps.

b. The digital baseband is QPSK modulated onto an IF carrier, with a noise bandwidth of 76.8 KHz.

c. A 140 KHz satellite channel bandwidth is considered for this service.

d. The minimum performance objective is a BER of 10^{-4}, with a C/N of 9.1 dB.

e. With a 4 dB C/N margin it is expected that the BER will be about 10^{-7} for 99% or more of the time.

D. INTERACTIVE MULTICHANNEL VOICE/DATA

In this configuration multiple carriers per transponder are shared by users in an FDMA system. For each voice/data link , a separate ground terminal is assumed. The earth stations for this service are locally maintained, redundant, receive/transmit earth stations, and they possess a limited test capability. Figure 2-4 is a typical block diagram representation of the Interactive Multichannel Data Service.

Signal Characteristics

Modulation parameters of this service are derived in Appendix 5.1, and are as follows:

a. The information bit rate for the interactive multichannel voice/ data is 768 Kbps.

b. The information baseband is rate 1/2 convolutional encoded to a 1.536 Mbps transmission bit rate.

c. The QPSK modulated carrier noise bandwidth is 921.6 KHz.

d. A 1.7 MHz satellite channel bandwidth is considered for this service.

e. The minimum performance objective is a BER of 10^{-4}.

f. With a 4 dB C/N margin a BER of 10^{-7} is expected for 99% or more of the time.

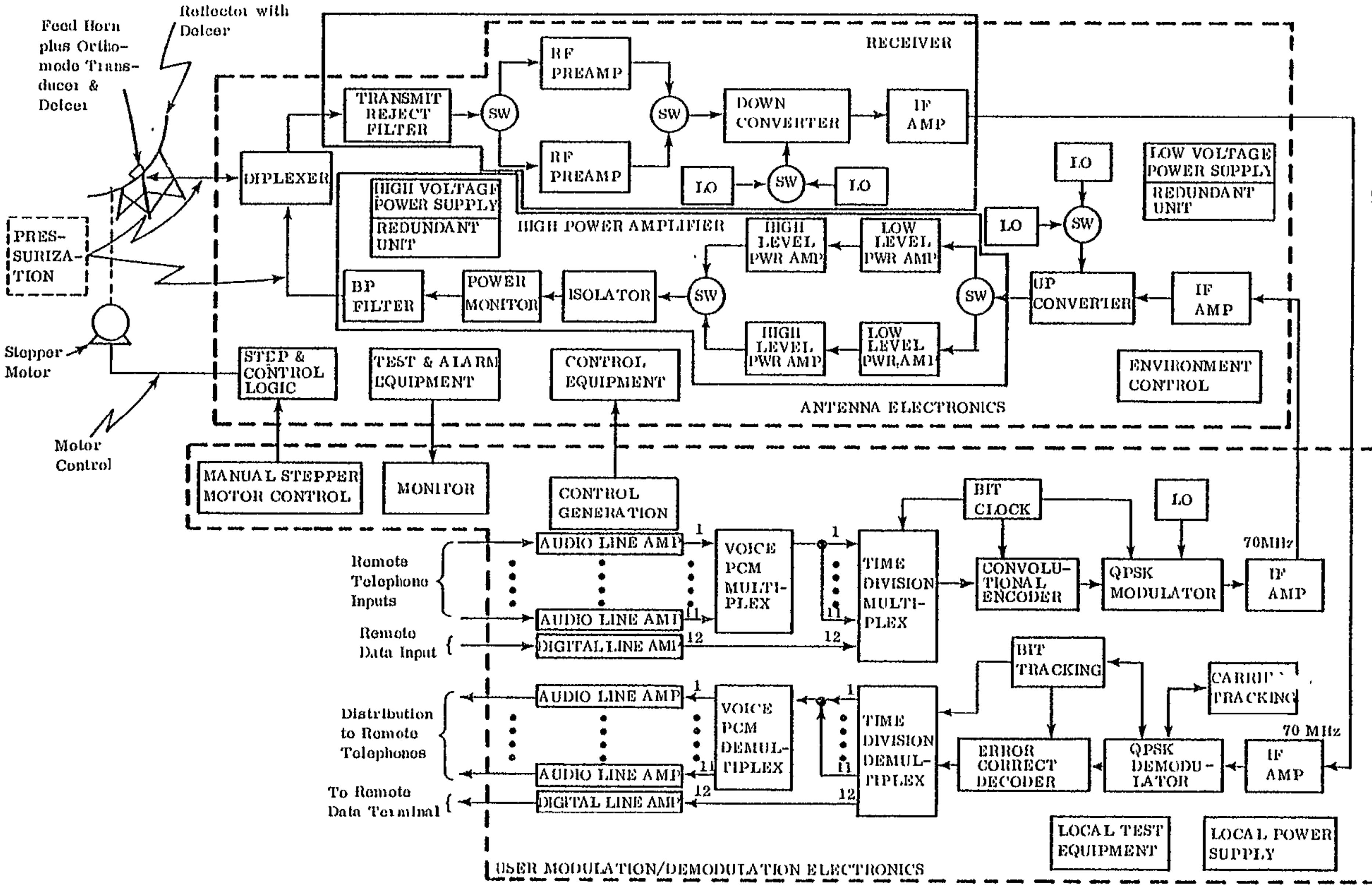

Figure 2-4 . Interactive (Two-Way) Multiplexer Voice and Data

2.6 BROADCAST SERVICES CONFIGURATION/CHARACTERISTICS

A. BROADCAST TV FOR LOCAL RETRANSMISSION

The system is configured to have a large number of receive only earth stations. The earth stations are locally maintained, unmanned, redundant, receive only earth stations, and they each have a limited test and control capability. Figure 2-5 is a typical block diagram of the broadcast TV for local retransmission earth station.

Signal Characteristics

The TV picture is generated by a 525 line TV signal whose frame rate is 30 frames/seconds. The modulation parameters are derived in Appendix 5.1; and are shown in Table 5-1. These characteristics are:

a. Maximum audio frequency; fm = 15 KHz

b. Maximum video frequency; F = 4.2 MHz

c. Audio subcarrier frequency; fsc = 6.5 MHz

d. Threshold video carrier-to-noise-ratio

$$\left[\left(\frac{C}{N}\right)_v\right]_{\text{Threshold}} = 12 \text{ dB}$$

e. Threshold audio carrier-to-noise ratio

$$\left[\left(\frac{C}{N}\right)_a\right]_{\text{Threshold}} = 12 \text{ dB}$$

f. Audio subcarrier bandwidth, Bsc = 245 KHz

g. TV signal predetection bandwidth, Bn = 32 MHz

h. The video peak-to-peak signal-to-rms weighted noise ratio, Spp/Nw = 50.6 dB. This Spp/Nw is a minimum requirement; and with a 7 dB carrier-to-noise ratio margin the Spp/Nw is about 57 dB for most of the time.

i. The audio test tone signal-to-weighted noise ratio, S/N = 43 dB This S/N is a minimum performance criteria, and with a 7 dB C/N margin the S/N is between 43 dB and 50 dB.

j. Peak video deviation due to the video, $\Delta Fp = 13.3$ MHz

k. Peak video deviation due to the audio, $\Delta Fc = 0.9$ MHz

l. Audio modulation index, Mz = 7.166

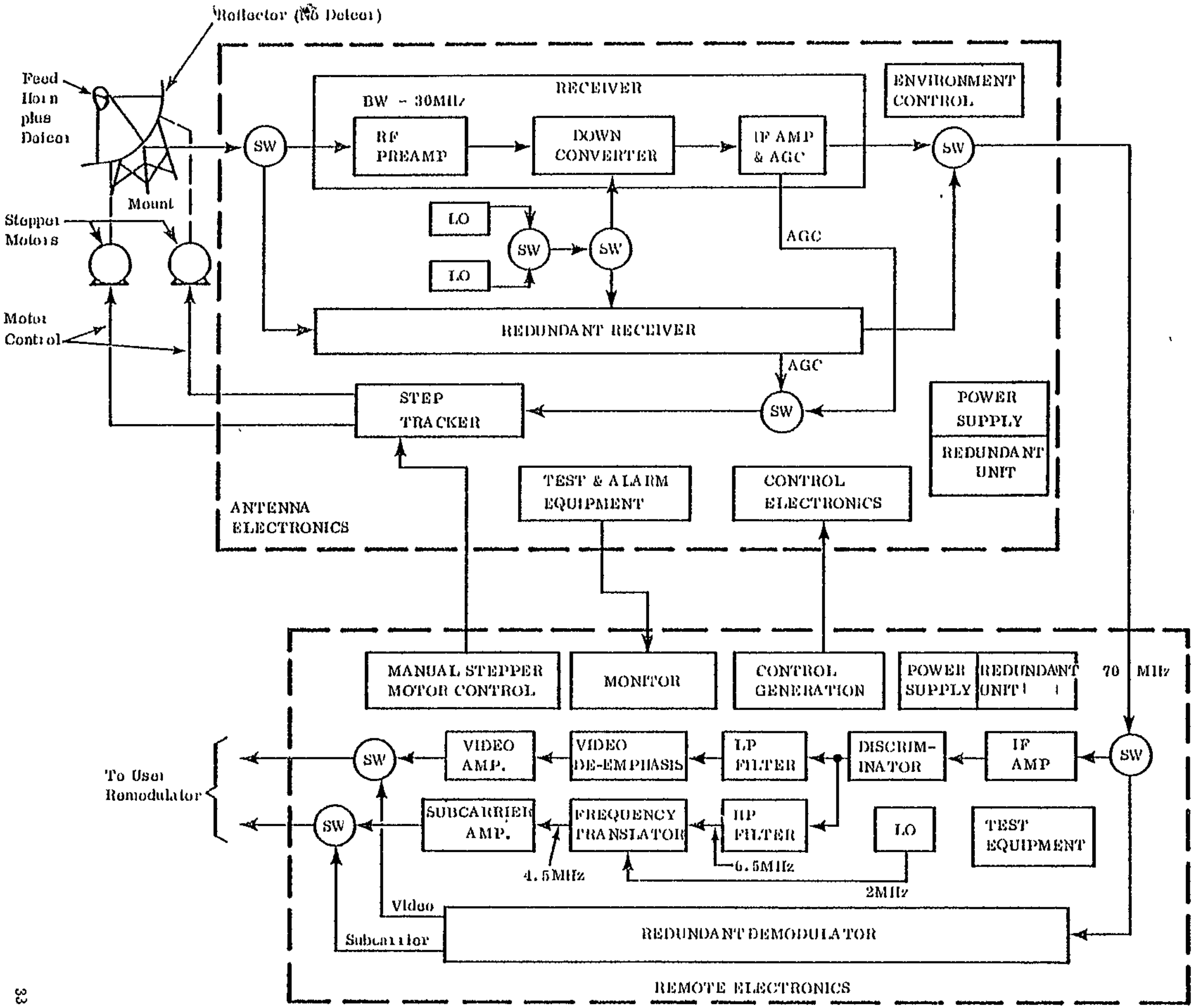

Figure 2-5. Receive Terminal (Broadcast TV for Local Retransmission)

B. BROADCAST TV DIRECT TO USER

In this system, a large number of receive only terminals are utilized. The earth stations are unattended, non-redundant receive only terminals. Figure 2-6 is a block diagram of the broadcast TV direct-to user earth station. Figure 2-7 is a block diagram of the remodulation system needed for compatibility with a home receiver.

Signal Characteristics

The TV picture is generated by a 525 line TV signal whose frame rate is 30 frames/sec. Modulation parameters are derived in Appendix 5.1, and are shown in Table 5-1. These characteristics are:

a. Maximum audio frequency, fm = 15 KHz

b. Maximum video frequency, F = 4.2 MHz

c. Audio subcarrier frequency, fsc = 6.5 MHz

d. Threshold video carrier-to-noise-ratio

$$\left[\left(\frac{C}{N}\right)_v\right]_{\text{Threshold}} = 12 \text{ dB}$$

e. Threshold audio carrier-to-noise ratio

$$\left[\left(\frac{C}{N}\right)_a\right]_{\text{Threshold}} = 12 \text{ dB}$$

f. Audio subcarrier bandwidth Bsc = 245 KHz

g. TV - signal predetection bandwidth, Bn = 22 MHz

h. The video peak-to-peak signal to rms weighted noise ratio, Spp/Nw = 40.17 dB This Spp/Nw is a minimum requirement, and with a 7 dB carrier-to-noise ratio margin the Spp/Nw is 47.17 dB for most of the time.

i. The audio test-tone signal to weighted noise ratio, S/N = 43 dB This S/N is a minimum performance criteria, and with a 7 dB C/N margin the S/N is 50 dB for most of the time.

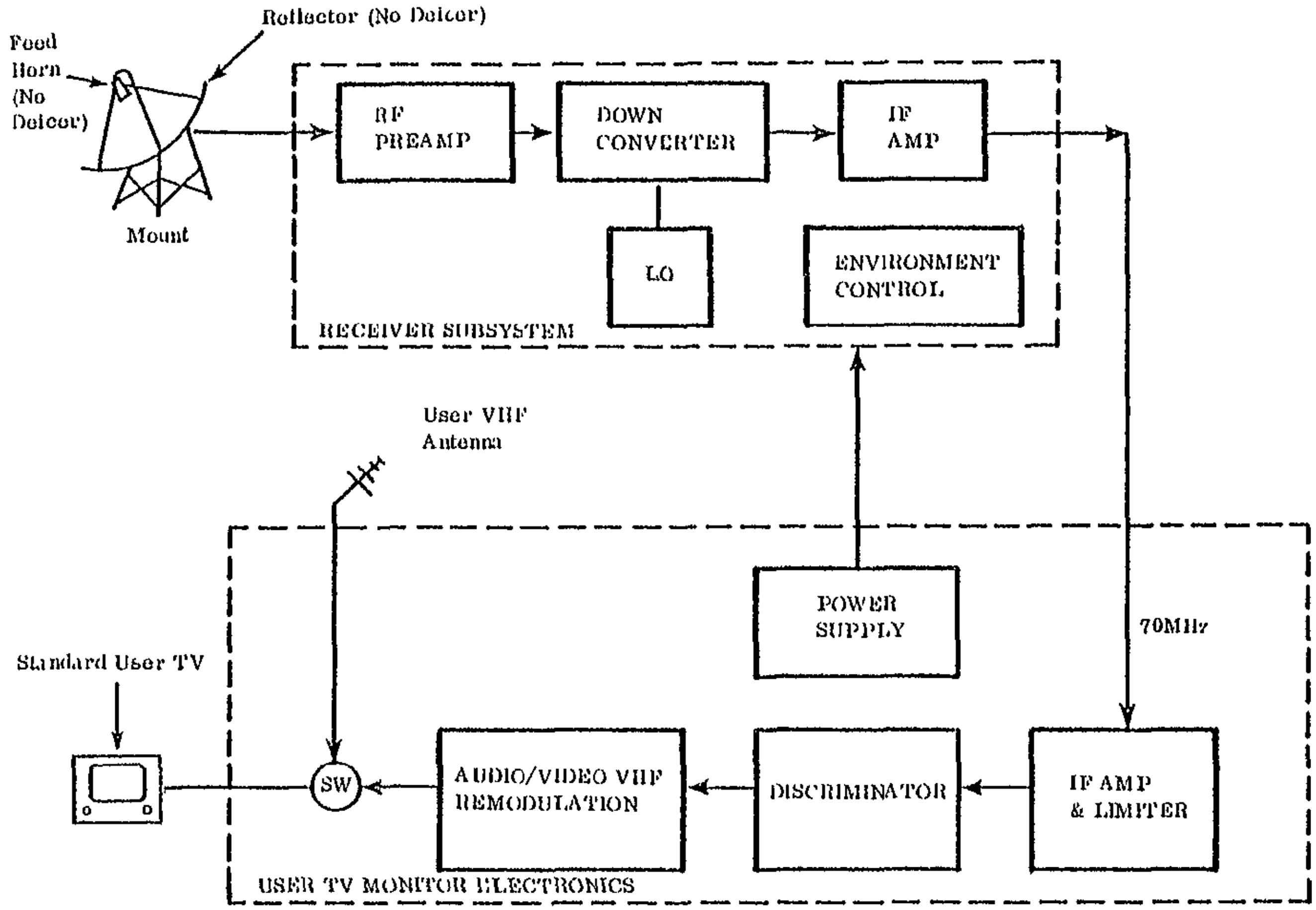

Figure 2-6 . Broadcast TV Direct to User

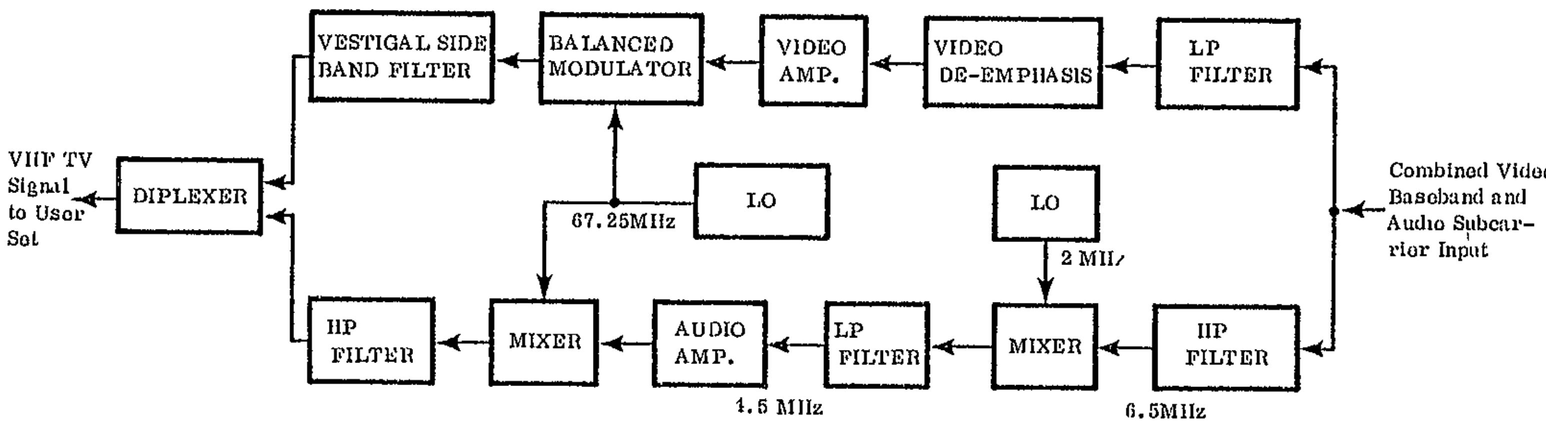

Figure 2-7 . TV Receiver Audio/Video VHF Remodulation Block Diagram

C. BROADCAST FM VOICE/MUSIC FOR LOCAL DISTRIBUTION

In this configuration a multiple carrier satellite transponder is shared by the users in an FDMA system. A large number of receive only ground terminals are utilized. The earth stations of the broadcast voice/music for local distribution service are locally maintained, unmanned, redundant, receive only earth stations. Figure 2-8 is a typical block diagram of the broadcast FM voice/music for local retransmission earth station.

Signal Characteristics

The modulation parameters of this service are derived in Appendix 5.1 and shown in Table 5-2. These parameters are:

a. Maximum baseband frequency; fm = 15 KHz

b. An FMFB threshold extension demodulation is used. The threshold carrier-to-noise ratio is 7 dB.

c. The modulation index M is 5.7

d. The channel bandwidth is 240 KHz

e. The test-tone signal-to-weighted noise ratio is at least 46 dB.

f. With a 7 dB C/N margin a 53 dB S/N is provided for most of the time.

D. BROADCAST COMPRESSED TV

The system is configured to have multiple carrier satellite transponders which are time shared by the users in an FDMA system. A limited number of receive only ground terminals are utilized. The earth stations are locally maintained, unmanned, non-redundant, receive only earth stations. Figure 2-9 is a block diagram of the broadcast compressed TV terminal.

Signal Characteristics

The TV picture is generated by a 525 line TV signal whose frame rate is 30 frames/second. Modulation characteristics for this service are derived in Appendix 5.1

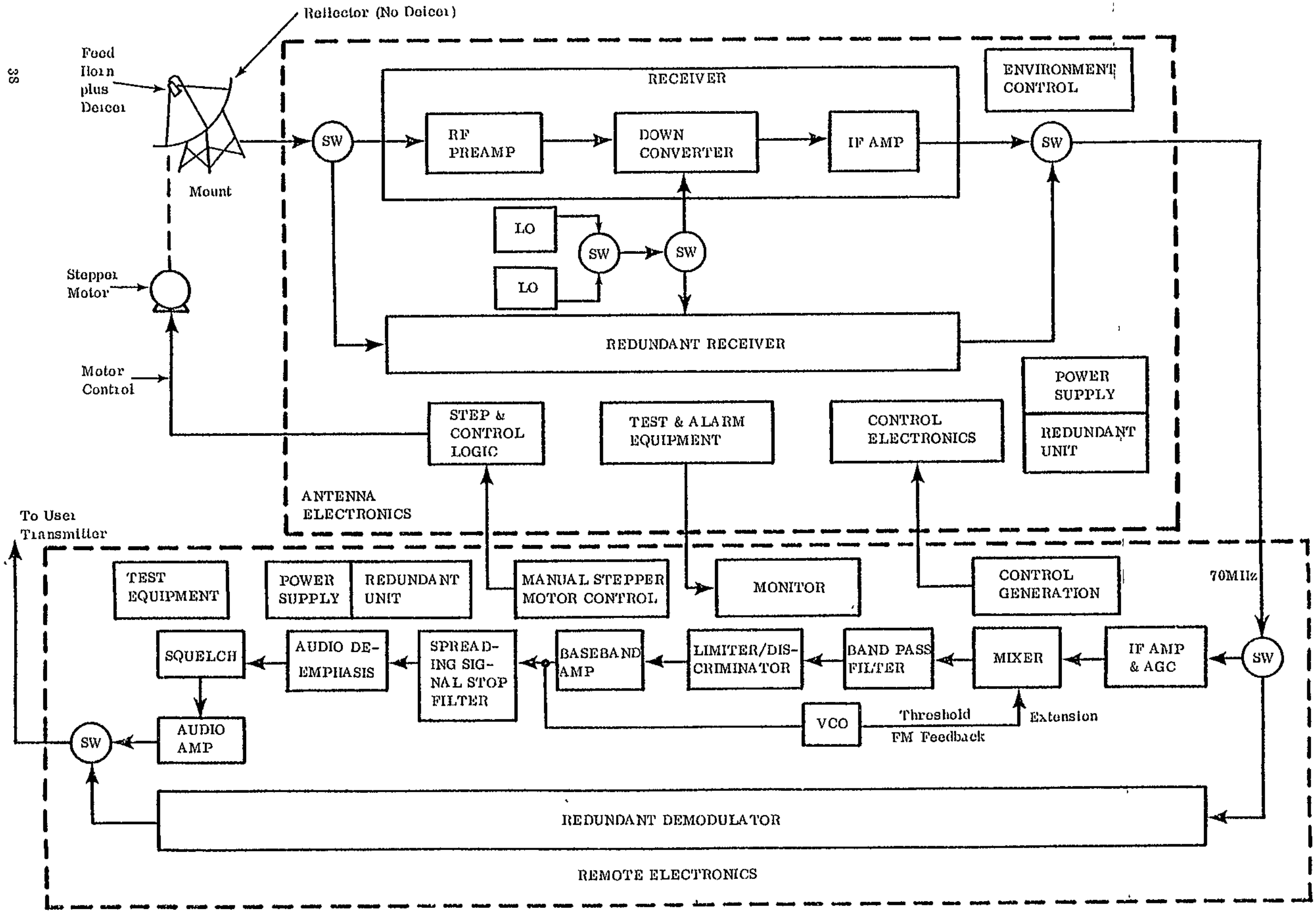

Figure 2-8. Receive Terminal (Broadcast FM Voice/Music for Local Retransmission)

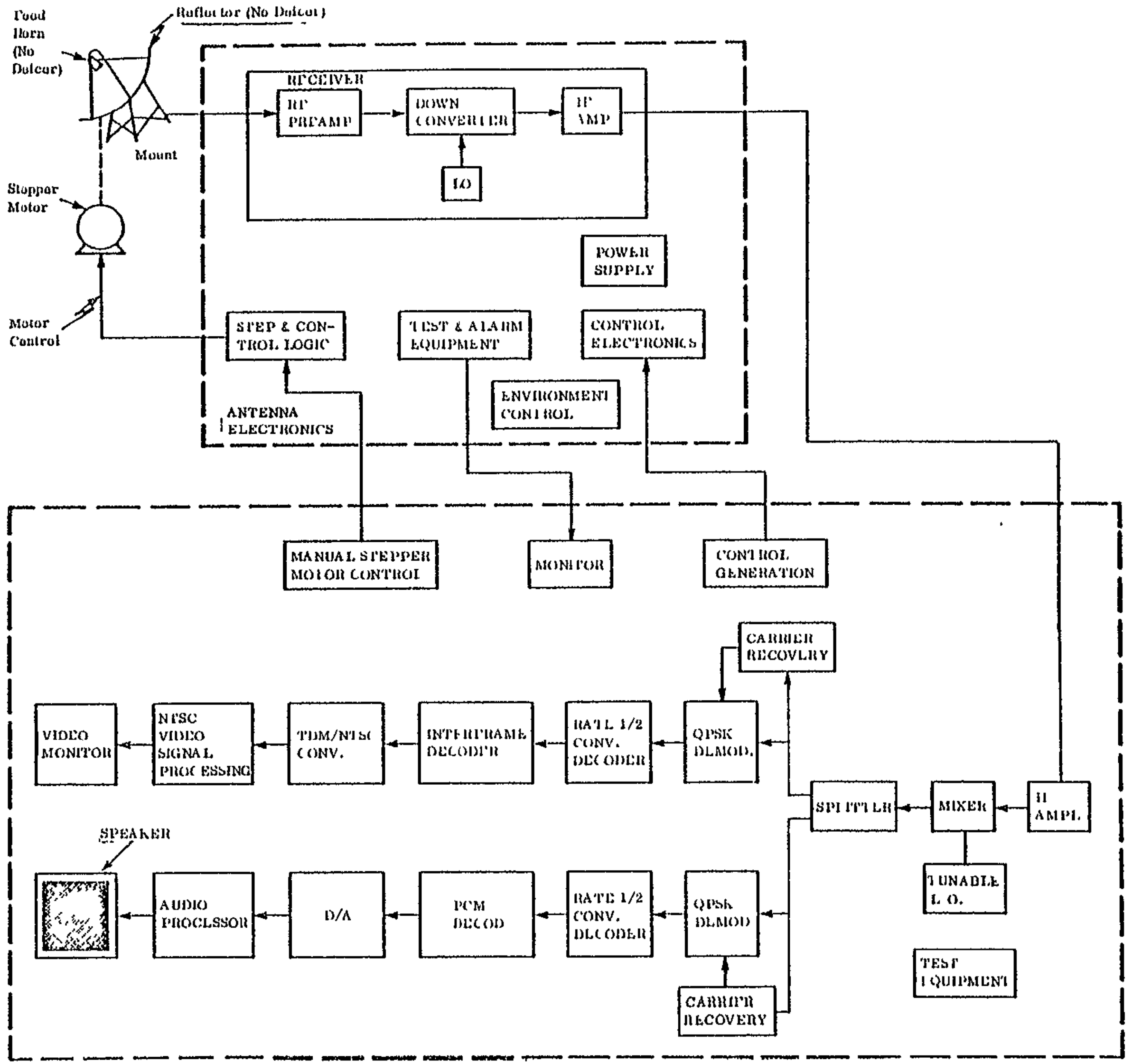

Figure 2-9. Receive Terminal (Broadcast Slow Motion TV for Local Use

and are shown in Table 5-2. These characteristics are:

a. Video interframe encoded bit rate is 6.3 Mbps.

b. Interframe encoded video baseband is rate 1/2 convolutional coded; and the resulting bit rate is 12.6 Mbps.

c. Digital video baseband is QPSK modulated on a video subcarrier. The modulated video subcarriers bandwidth is 7.56 MHz.

d. The uncoded audio signal is a 64 Kbps PCM signal.

e. The PCM audio signal is rate 1/2 convolutional coded to a bit rate of 128 Kbps.

f. The audio digital baseband is QPSK modulated onto an audio subcarrier. The modulated audio subcarrier noise bandwidth is 74.4 KHz.

g. A 12 MHz TV channel bandwidth is considered for the combined audio and video signals.

h. The minimum performance objective is a BER of 10^{-4} with a C/N of 9.1 dB.

i. With a 4 dB C/N margin the expected BER is 10^{-7} for most of the time.

E. BROADCAST FM VOICE/MUSIC DIRECT TO USER

In this configuration a single satellite transponder is shared by the users in an FDMA system. A large number of receive only earth stations are being utilized. The earth stations are unattended, locally maintained, non-redundant receive only terminals. Figure 2-10 is a typical block diagram of the Broadcast FM Voice/Music Direct to user service.

Signal Characteristics

Modulation parameters for this service are derived in Appendix 5.1 and are shown in Table 5-2. These parameters are:

a. Maximum baseband frequency fm = 8 KHz

b. An FMFB threshold extension demodulator is used. The threshold carrier to noise ratio is 7 dB

c. The modulation index M is 3.9.

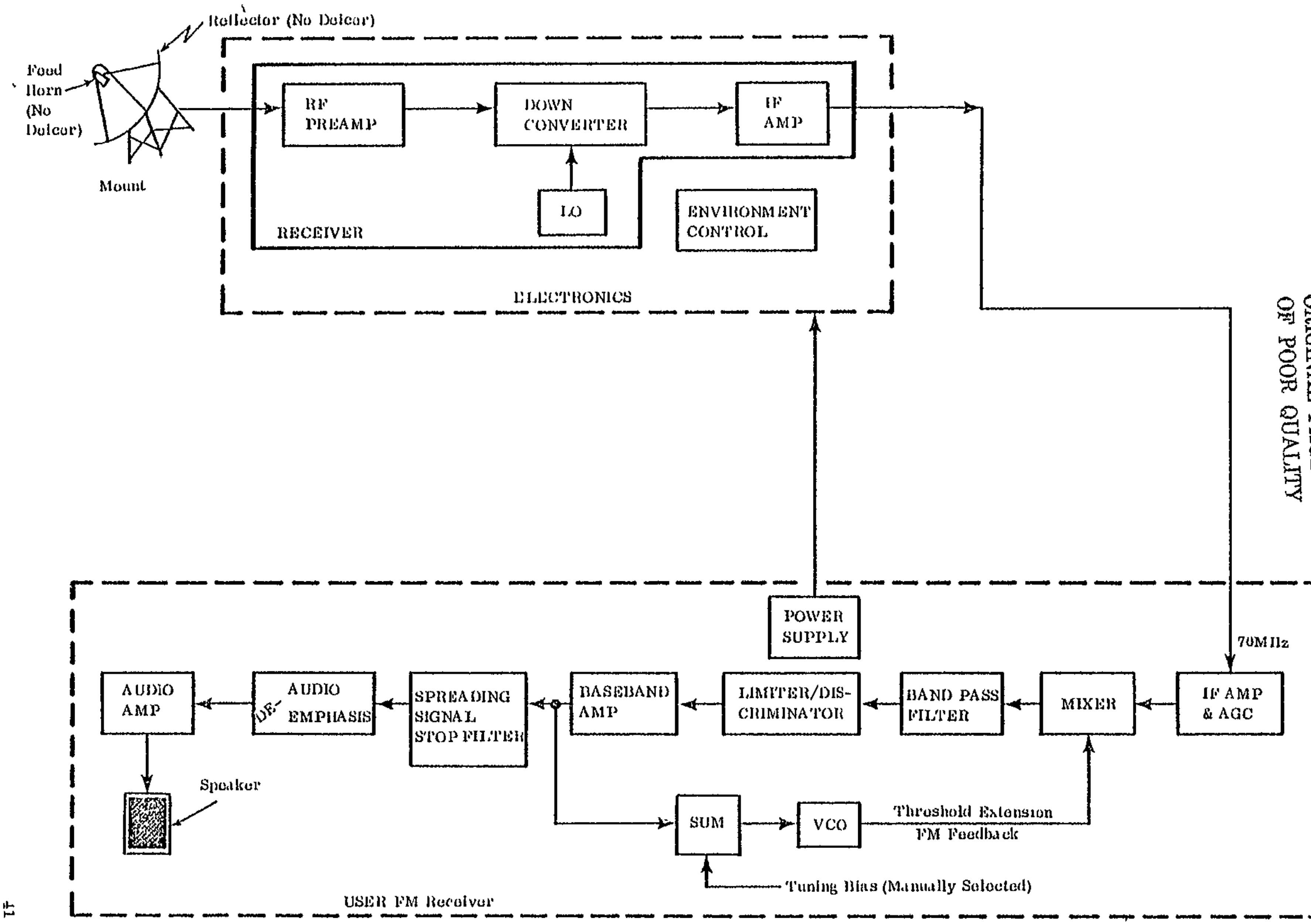

Figure 2-10. Receive Terminal (Broadcast Radio (Voice/Music) Direct to User)

d. The channel bandwidth is 100 KHz.

e. The test-tone signal-to-weighted noise ratio is at least 40 dB.

f. With a 7 dB C/N margin a 47 dB S/N is provided for most of the time.

2.7 THE LAND MOBILE SATELLITE SERVICE

A. THE PRESENT LAND MOBILE RADIO SYSTEM

Terrestrial two way mobile radio systems have been in operation for several decades. In the last few years high performance state of the art mobile radios have been provided by the mobile radio industry. In order to handle this, terrestrial mobile communication traffic, repeaters, base stations and central office control, e.g., Mobile Telecommunication Systems (MTSs) have been built.

Presently a High Capacity Mobile Telecommunication System (HCMTS) is being developed to accommodate the growing urban and inner city needs. In order to improve the mobile telephone service, new mobile telephone service, new mobile telephone control terminals are being provided for the Improved Mobile Telephone System (IMTS). The present day land mobile radio equipment is discussed in Appendix 1, Section F.

The Operational Concept of the Present Mobile Radio System

The present land mobile radio system is a multi-access system. In this system, a number of users are being serviced through the shared use of a few base radios. Figure 2-11 shows the block diagram of a multi-access mobile radio system. In this system, the user's radio is equipped with all the usual telephone signalling modes. For example, if a radio channel (of a trunk) is busy, the user's own radio will furnish a "busy" tone. A maximum of 8 to 12 radio channels per user's radio are used. Initially the mobile radios had less than 8 radio channels, however, expansion to 8 or 12 channels is possible by the addition of "plug in" crystal oscillators.

The base station serves as a relay between the mobile radio user and the telephone exchange terminal. A block diagram of the exchange terminal is shown in Figure 2-12. The exchange terminal is equipped with Line Termination Modules and Channel Link Modules. There is a Line Termination Module for each line (or trunk) in the system. Each Line Termination Module is extended by a radio. For each base radio in the system there is a Channel Link Module. The Line Termination Modules and the Channel Link Modules are housed in the Line Termination Card Cage and in the Channel Link Card Cage respectively.

Each Line Termination Card Cage accommodates Line Termination Modules for 10 user line circuits. For example, if a user line (or a trunk) is shared by 7 users; then each line termination module handles 1 line of 7 users, and each Line Termination Card Cage can accommodate up to 10 Line Termination Modules of 70 users. Each Line Termination Card Cage is also supplied with one Master Distribution Module. The Master Distribution Module is used to interface with the telephone network. To accommodate an

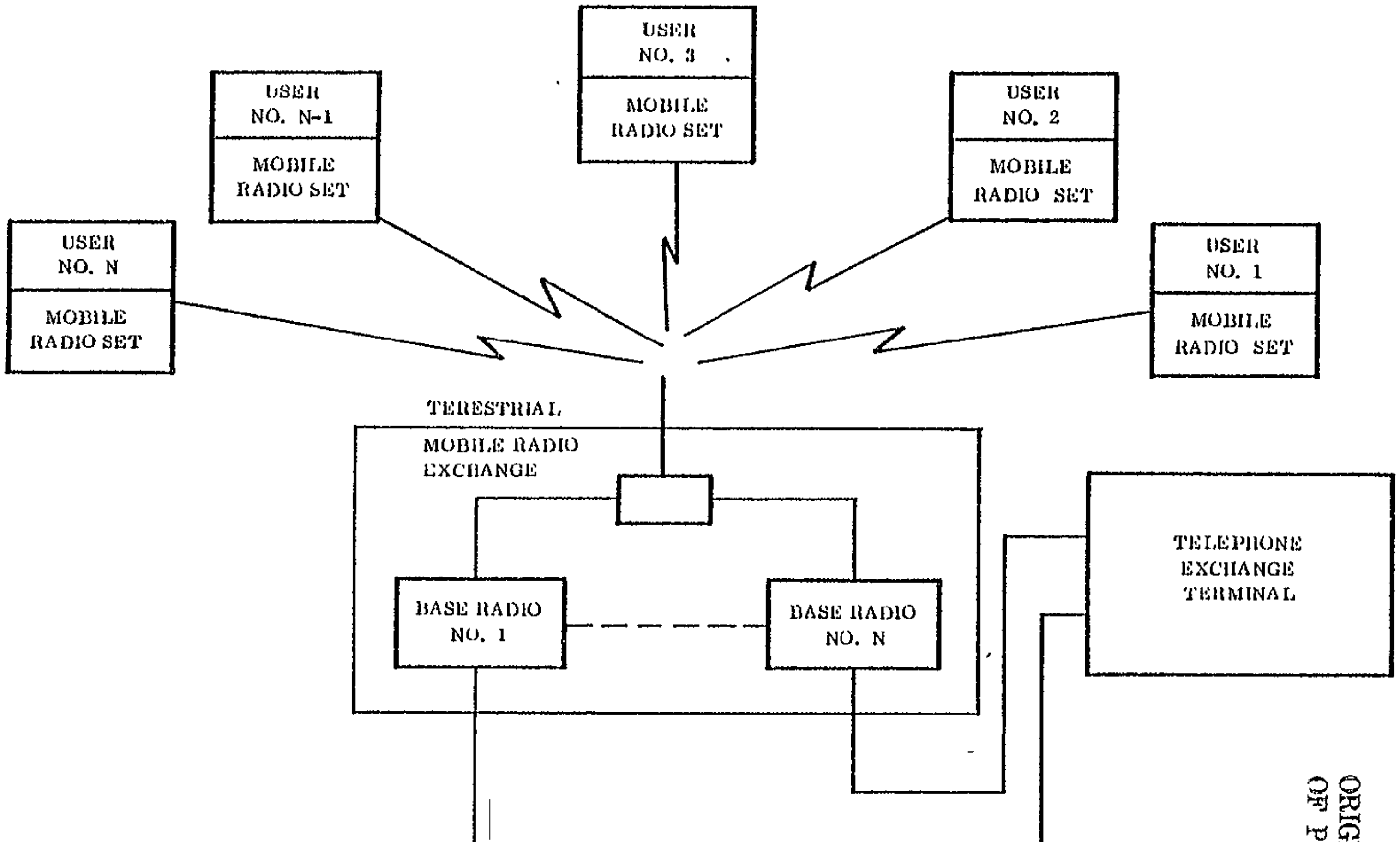

Figure 2-11. Multi-Access Mobile Radio System
(Note: there are N base radios used in conjunction with N user Mobile Radios)

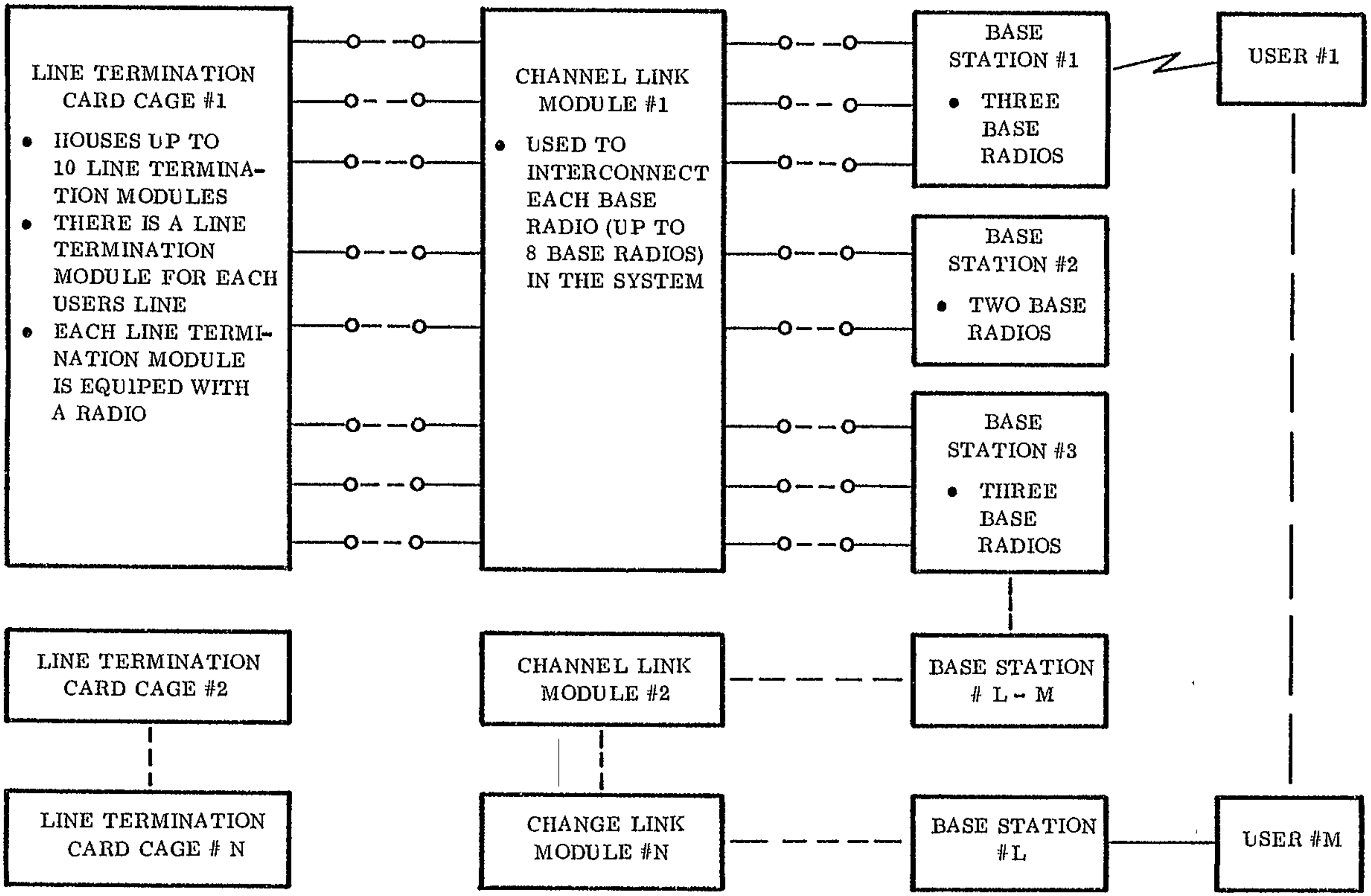

Figure 2-12. Block Diagram of the Terestrial Mobile Radio Communication System

increase in the number of mobile radio users an additional Line Termination Card Cage is added for each additional 10 user lines. The Channel Link Card Cage contains a Channel Link Module, which interconnects each base radio in the system.

2. The Signaling Arrangement of the Present Multi-access Mobile Radio System

The system automatically selects a free channel and it provides signaling only to the desired customer. For example, a four-digit code is assigned to each user radio and to its associated line termination unit. (it is appropriate to note here that mobile radios with up to 7 digit codes are available). These codes are transmitted on the "signaling tones", which can be arranged in the following manner:

TONE CODE	FREQUENCY	TONE CODE	FREQUENCY
R	487	6	1387
1	637	7	1537
2	787	8	1687
3	937	9	1837
4	1087	0	1987
5	1237	C	2137

Each tone is used to identify one digit out of the user's identification code (or mobile radio phone number). Both the users radio and the line termination module at the exchange are programmed with the same identification code. The "R" and "C" tones provide the supervisory and control functions. The signaling sequence for placing a call between the exchange to the user and from the user to the exchange are shown in Figures 2-13 and 2-14, respectively. The tones are used sequentially, and they are used only during signaling and supervision intervals.

When the user's radio is not in use the receiver logic continually steps the local oscillator from frequency to frequency. When an RF carrier is received in one of the scanned frequencies. the receiver logic determines whether or not it is the user's identification code. If it is not identified as the user's code, then the receiver continues to scan. When the correct code is received, the receiver stops scan and the transmitter is turned on. The user's radio automatically sends its code back to the exchange. This "handshaking" or round trip test is accomplished while the user's set is still idle (or "on-hook"). At the time of the call initiation, the exchange is placing a ringing signal on the selected user's RF frequency. After the "handshaking" takes place the ringing signal is heard by the user. This ringing signal is generated by the "R" and "C" tones (See Figure 2-13). When the user acknowledges the call (lifts off the handset) "R" and "C" tones are generated by the user's radio. The exchange upon reception of the "R" and "C" tones connects the calling party to the user's mobile radio set, and a call is established.

When the user initiates a call, he lifts the handset from the hook. and with this he turns on his transmitter. The idle voice channel for transmission has previously been selected by the receiver logic which has been continuously scanning in search of an

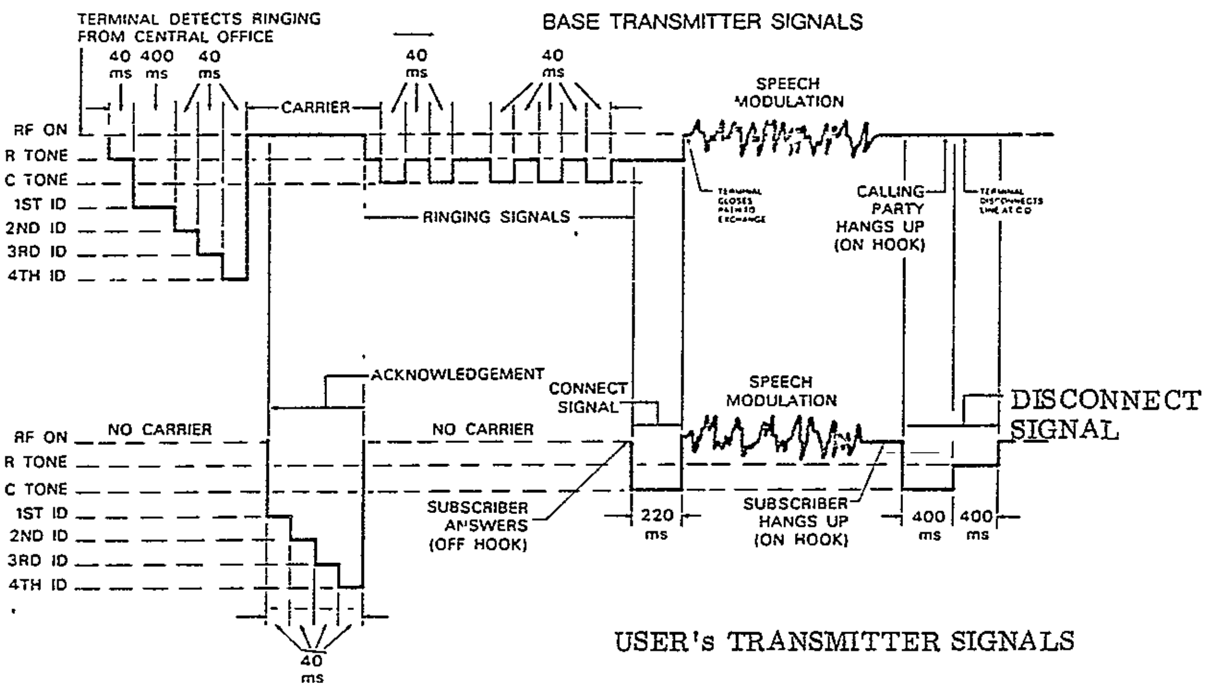

Figure 2-13. Signaling Sequence For Exchange-Orginated Calls

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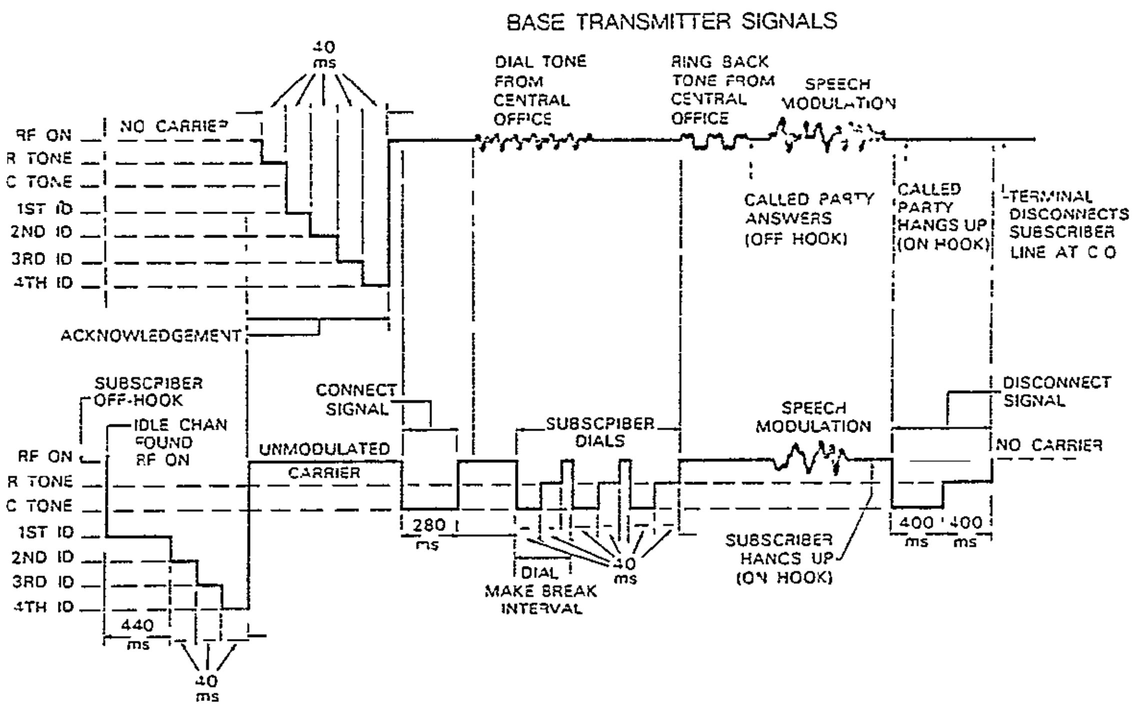

Figure 2-14. Signaling Sequence For User Orginated Calls

idle channel. At the instant when the user's radio has turned on, it transmits the user's identification code. When the exchange recognizes the user's call attempt, it sends back the users identification code, and again a "handshaking" procedure takes place. After "handshaking" the user's logic sends a "connect" signal utilizing the "R" and "C" tones. The exchange generates an audible tone which indicates the user is ready to dial. The user dials the same way as he would a regular telephone set. After dialing there is a "ring back" signal sent from the exchange, and subsequently the parties are connected for their call. When one of the users "hang up" a disconnect signal is sent by means of the "R" and "C" tones. Thus all signaling, ringing, supervisory, and control functions are the same as in a regular telephone set.

3. Performance Characteristics of the Present Mobile Radios

a. With a 12 dB SINAD ratio the sensitivity is 0.25 uV to 0.35 uV; and with a receiver preamplifier a sensitivity of 0.175 uV is available (See Appendix 1, Section F, for specification of present day mobile radios). The term SINAD ratio is defined in the EIA standards, and its definition is given as: The SINAD ratio is "A measure expressed in decibels of the ratio (1) the signal plus noise plus distortion to (2) noise plus distortion produced at the output of a receiver that is the result of a modulated signal input." The SINAD sensitivity is "the minimum standard modulated carrier signal input required to produce a specified sinad ratio at the receiver output." The 12 dB SINAD is equivalent to a 3 dB IF carrier to noise ratio, C/N.

b. The channel spacing at the UHF frequencies is 25 KHz. The signal noise bandwidth is at most 20 KHz.

c. Audio distortion is 2% to 5%.

d. RF output impedance is 50 ohms.

e. The modulation deviation is ±5 KHz to ±7KHz.

f. Frequency stability is at least ±0.0005%.

g. An omnidirectional antenna with a gain of about 0 dB to 5 dB is used.

h. Transmitter powers of 10 watts to 65 watts are available.

i. The mobile radio noise temperature can be estimated from the expression, (in decibels)

$$T = C - \frac{C}{N} - K - B$$

Where $\frac{C}{N}$ = SINAD −9 dB

T = Mobile Radios Noise Temperature (^{o}K)

C = Carrier signal power at the receiver's input

K = Boltzman Constant = -228.6 dB/watts/degree/Hz

B = Receiver noise bandwidth = 20 KHz

$$C = \frac{(\text{Modulated Carrier Signal Input (in uV)})^2}{\text{Input Impedance}}$$ where the input

Impedance = 50 ohms.

With a receiver preamplifier the modulated carrier signal input is 0.176 uV. Thus, the carrier power can be approximated as:

$$C = \frac{(0.175 \times 10^{-6})^2}{50} = 6.125 \times 10^{-16} \text{ Watts (i.e. } C = -152.13 \text{ dBw)}$$

The mobile radio noise temperature T is given by:

$$T = -(152.13 + 3 + 43) + 228.6 = 30.47 \text{ dB } ^{o}K$$

Thus, if we assume a correction factor of 2.5 dB^{o}K, then the mobile radio noise temperature is 2000^{o}K. In this study it is assumed that the mobile radios (with a receiver preamplifier) have a noise temperature of 2000^{o}K.

j. The output signal-to-noise ratio is given by: (See Appendix 5.1)

$$\frac{S}{N} = \frac{3}{2} \left(\frac{f}{fm}\right)^2 \left(\frac{B}{fm}\right) \left(\frac{C}{N}\right) \cdot I$$

Where fm = Voice Channel baseband bandwidth = 3.1 KHz

B = Noise bandwidth = 20 KHz

$\frac{C}{N}$ = 12 dB

I = Total Improvement (I consists of pre-emphasis plus weighting plus companding improvements) (i.e. 16.5 dB)

f = Peak frequency deviation = $\pm$5 KHz

The output test-tone signal to weighted noise ratio S/N is 42.5 dB.

It is appropriate to note here that according to CCIR Rec. 533-2 the S/N requirement is 43 dB for at least 99.7% of the time, and for at least 80% of the time a S/N of 50 dB is required.

B. THE SATELLITE LAND MOBILE RADIO SYSTEM

1. System Concept

The UHF land mobile satellite service is assumed to be provided in the 620 MHz to 790 MHz frequency band. The uplink frequency band will occupy the band from 709.5 MHz to 790 MHz.

Since this service will be mainly used in areas outside urban centers, the communication traffic is between a mobile user and a fixed location having access to the nationwide telephone network. The overwhelming majority of traffic requirements from mobile user to mobile user are within a relatively small geographical area. This type of traffic is already handled (or planned to be handled) by other means, for example, by the "cellular mobile radio" concept, by the CB radio concept, or by the local telephone networks.

The UHF land mobile radio can be connected to the nationwide telephone network via several larger Communication Routing Terminals (CRT's). The CRT's use Ku-band and will be situated across the country. Calls from the UHF mobile radio are received by the satellite in the UHF uplink band, translated to the 12 GHz downlink band for relay to a CRT. The CRT connects the calls to the nationwide telephone network. The return path is from the nationwide telephone network to the CRT and thence to the satellite via the 14 GHz uplink frequency band. In the satellite the call is translated to the UHF downlink frequency for broadcast to the mobile user. For conversation between mobile users, both having UHF sets, the number of passes through the satellite is doubled. However, it is expected that the mobile to mobile user calls will be at a minimum.

The overall advantages of the above configuration are:

- All signal processing is performed on the ground so that the satellite transponder weight is reduced.
- Provisions can be made to update signal processing methods during the life of the satellite.
- Since, a Ku-band CRT has a relatively high earth station sensitivity figure of merit (G/T), the downlink Ku-band portion of the satellite transponder can operate with substantially less power than the UHF downlink.

- The Ku-band antennas can be "rooftop" size allowing mounting on buildings within urban areas.
- With frequency coordination and additional antenna mounting, the Ku-band terminals also can be used as communication rerouting centers, e.g. CRT's.
- The Ku-band portion of the link can provide six times as much usable frequency band as the UHF portion. Thus, Ku-band can be advantageously adapted to provide a nationwide connectivity for the UHF land mobile user. For example, a 4 beam Ku-band antenna can provide about the same coverage as a 25 beam (120') UHF antenna.
- Billing, control and system modifications are relatively easy to accomplish.

2. The Capacity of the Land Mobile Satellite Service

The land mobile satellite service system capacities for the four distinct satellite antenna alternatives considered in this study are shown in Table 2-1. The system capacities of the table are maximum system capacities and are derived in Appendix 5.4.

3. Access In The Land Mobile Satellite Communication System

The satellite land mobile system is a single channel per carrier (SCPC) demand assigned multiple access (DAMA) system. In this SCPC-DAMA system, the users are being served by the shared use of the satellite and the Ku band earth stations. The user has complete privacy. For example, when a channel is busy the user will receive a "busy" tone. Figure 2-15 shows the block diagram of the communication paths of the SCPC-DAMA land mobile satellite communication system. These paths are: 1) the path from the UHF mobile user to the fixed user or the urban mobile user, 2) the path from the fixed user or the urban mobile user to the UHF mobile user, and 3) the path from the UHF mobile user to the UHF mobile user. In this system (just like in the terrestrial mobile radio system) the user's radio is equipped with all the usual supervisory and control telephone signalling modes. The satellite serves as a relay between the UHF mobile radio user and the Ku band earth station. The Ku band earth station is used as an interface between the telephone exchange (or other terrestrial systems) and the satellite.

4. The Communication Rerouting Terminal (CRT)

The Communication Rerouting Terminals (CRTs) operate in the 11.7 to 12.2 GHz downlink and the 14.0 to 14.5 GHz uplink bands. In Table 2-1 it is shown that the minimum capacity land mobile satellite system can accommodate up to 160,000 users. For each 160,000 users 3200 satellite channels (distinct frequency or trunks are used.

Table 2-1. The Capacity of the Land Mobile Satellite Communication Service for the Various Satellite Antenna Alternatives Considered in This Study.

Satellite Antenna Diameter	Number of Contiguous Beams $2.5^\circ \times 6^\circ = 15^\circ$ Square	B (MHz)		Number of Users In the System	
		Single Polarization	Dual Polarization	Single Polarization	Dual Polarization
210'	77	2066	3099	4,106,334	6,159,502
201'	25	671	1006	1,333,664	1,999.502
60'	6	161	242	320,000	480,000
30'	2	80.5	161	160,000	320,000

Note: 1. The probability of loss or blocking of calls (P) is computed from the Poisson equation ($P = e^{-y} \sum_{n=1}^{\infty} (y^n/n!)$; n = number of frequency slots or trunks and y = traffic offered in erlangs).

2. P = 0.01 (or the grade of service is 1 in 100)

3. n = 48 frequency slots per user.

4. For a bandwidth B = 25 KHz per frequency slot, there are at least 3200 frequency slots per each 80.5 MHz UHF bandwidth.

5. No. of Users = 2 x (UC) where UC = Unit Calls.

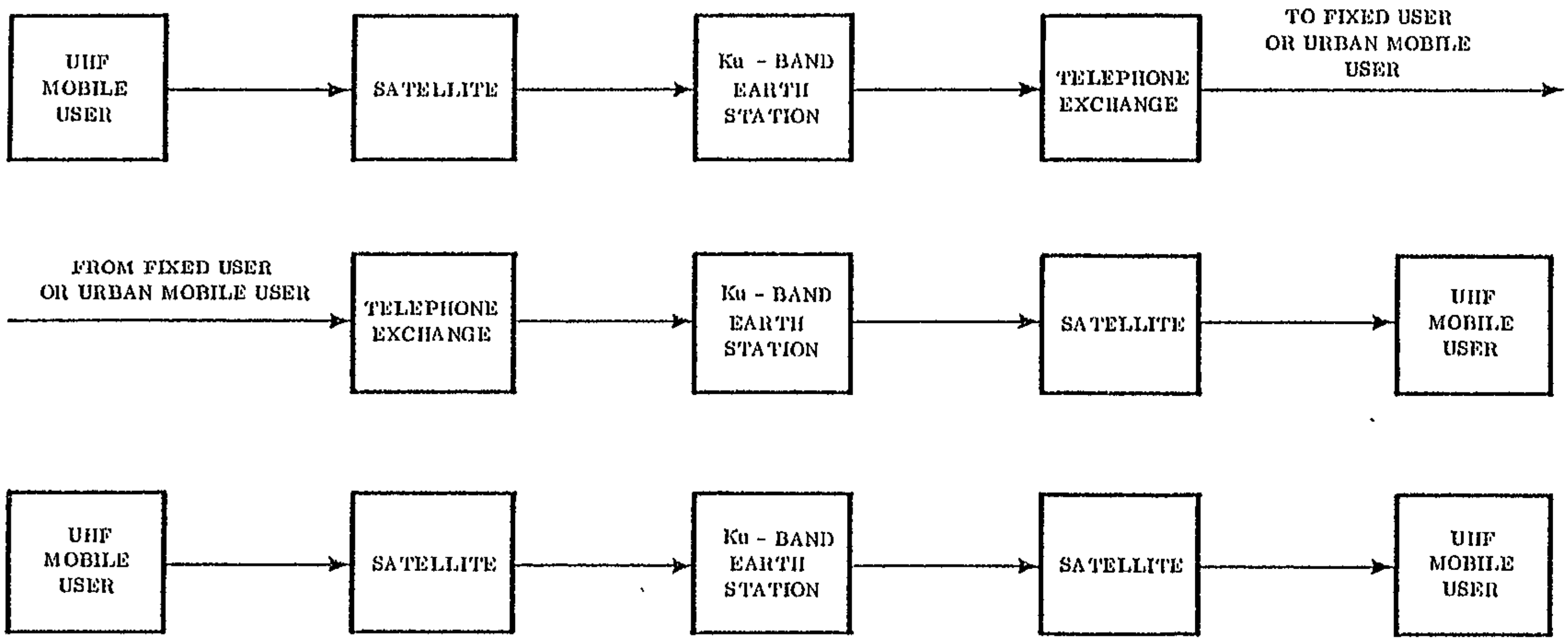

Figure 2-15. The Four Communication Paths of the Launch Mobile Satellite

For capacities greater than 160,000 users, the number of satellite channels (or trunks) are given by:

$$\left(\begin{array}{l} \text{The Received Number of} \\ \text{Trunks of A Given Configuration} \end{array} \right) = (\text{No. of Users}) \ X \left(\frac{3200 \text{ lines}}{160,000 \text{ users}} \right)$$

The multiple beam antenna alternatives (of this study) provide an increase in the effective UHF satellite bandwidth. The number of users and their corresponding number of satellite channels (or trunks) are linearly related to the available effective UHF satellite bandwidth (See Table 2-1). It is desired that the terrestrial tail be limited to an average 100 mile long land line. If the U.S. is covered by 100 CRTs, then the Ku band earth stations are about 200 miles apart thus providing an average tail length of 100 miles.

For the minimum capacity system 3200 satellite channels (trunks or frequency slots) are used (See Table 2-1 and Appendix 5.4). With 100 CRTs, each having on the average a 100 channel capacity, it is expected that at least a 2 to 1 redundancy in the channel availability of an individual CRT can be achieved. When the capacity of the system (and the number of satellite channels) is increased; the number of channels per CRT is increased by a factor of the ratio of the number of users to 160,000 users. That is the average number of channels of a CRT for a given satellite antenna alternative is given by:

$$\left(\begin{array}{l} \text{The Number of lines} \\ \text{per Earth Station} \end{array} \right) = 100 \quad x \quad \left(\frac{\text{Number of users}}{160,000 \text{ users}} \right)$$

The average number of lines per CRT for the different satellite antenna alternatives of this study are given in Table 2-2. A more accurate channel number allocation for each CRT will depend upon the traffic densities of the individual CRT locations.

The Ku band CRT is shown on Figure 2-16. The earth stations of this service are fully redundant with receive and transmit capabilities (note, the CRT redundancy is not shown on Figure 2-16). The received signal is preamplified and down-converted to a 70 MHz IF carrier. The up and down converters are controlled by the pilot reference frequency which is sent by the master station, the Communication Management Facility (CMF). The CMF communicates with each CRT in the TDMA mode through each one of the individual CRT system computers. The CMF also sends a status check on the current pilot frequency. The CRT's system computer in conjunction with the pilot reference generator checks the status of the received pilot frequency. Furthermore, the CRT's system computer also sends a periodic status report to the CMF; and the sent report also includes the received pilot frequency status. If the received pilot frequency is unacceptable then the CRT's system computer immediately relays this information to the CMF.

Table 2-2. The Required Number of Voice Channels (or trunks) for The Land Mobile Satellite System Satellite Antenna Alternatives

Satellite Antenna Diameter	Number of Contiguous Beams $2.5^{o} \times 6^{o} = 15^{o}$ Square	B (MHz)		No. of Satellite Voice Channel (or trunks)		No. of Unit Calls (UC's) per busy hour (or the number of users)		Average No. of Voice Channels (or trunks) Per CRT	
		Single Polarization	Dual Polarization	Single Polarization	Dual Polarization	Single Polarization	Dual Polarization	Single Polarization	Dual Polarization
210'	77	2066	3099	82,127	123,191	4,106,334	6,159,502	2,567	3,850
120'	25	671	1006	26,674	39,991	1,333,669	1,999,502	834	1,250
60'	6	161	242	6,400	9,600	320,000	480,000	200	300
30'	2	80.5	161	3,200	6,400	160,000	320,000	100	200

Note: 1. The Number of users are based on Table 2-1 and Appendix 5.

2. 100 CRTs are considered.

3. 50 users per satellite voice channel (or frequency slot) are considered.

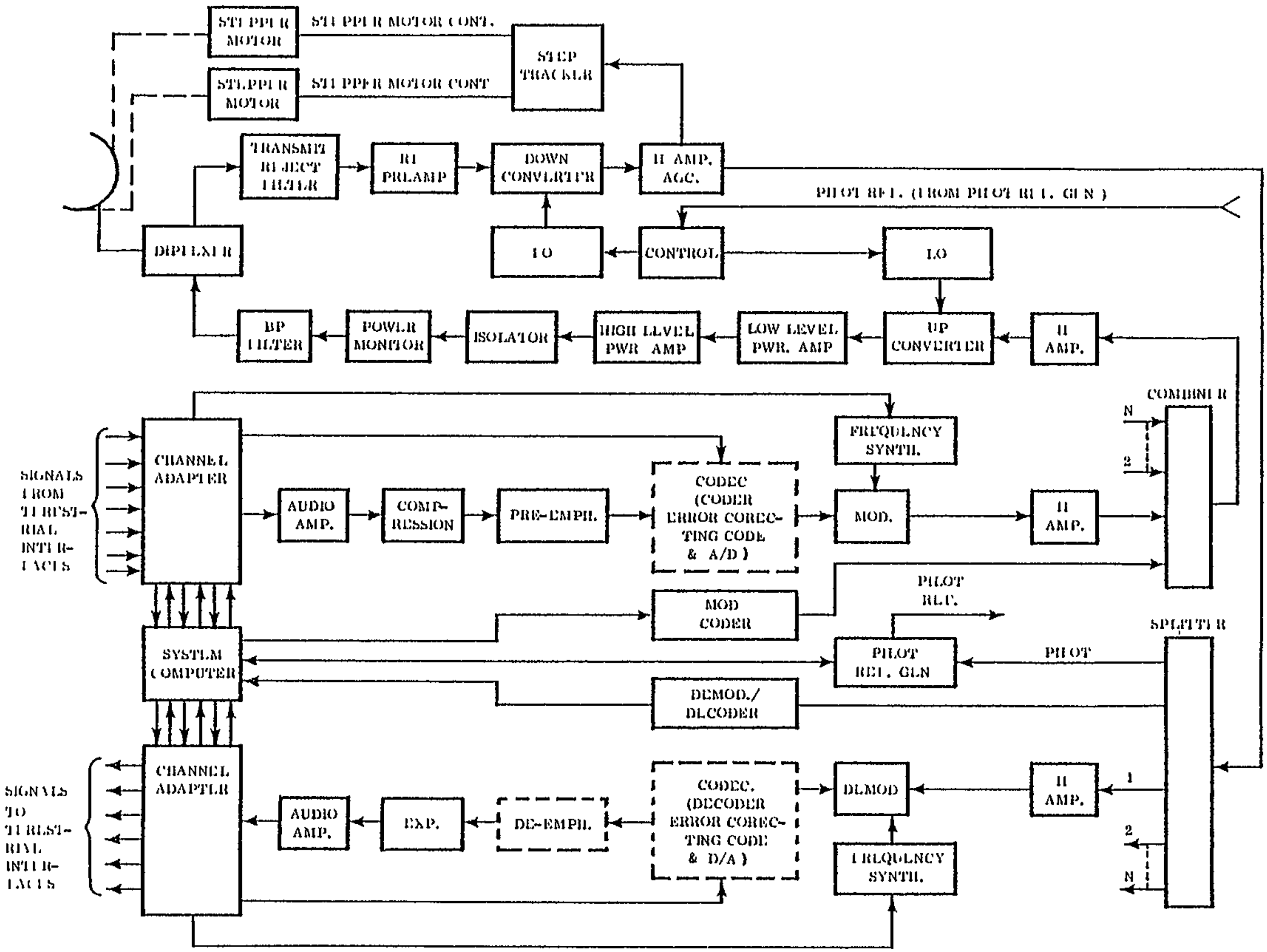

Figure 2-16. Communication Re-routing Terminal for the Land Mobile Satellite System

On the receive side the 70 MHz IF carrier signal is amplified, then passed to a splitter and to the AGC circuit. The AGC signal is used as the control input to the Ku band antenna step tracker, (the antenna step tracker operation is described in Appendix 5.2) In the splitter the IF signal is divided among several demodulators. The demodulator frequency is set by the frequency synthesizer which continuously scans (both at the modulator and at the demodulator) an average number of 32 frequencies (per voice channel). The control signals to the frequency synthesizer are sent by the channel adapter's logic, which interfaces with the CRT system computer. When a signal is present on one of the scanned frequencies. the channel adapter (along with the frequency synthesizer) stops the scanning for that voice channel. The modulator frequency is synchronous with the demodulator frequency. Thus, when a frequency (or satellite channel) is seized on the receiving side, the corresponding transmission frequency also is assigned. Similarly, when an outgoing frequency has been assigned. then the corresponding incoming frequency is also automatically assigned.

With adaptive delta modulation (ADM) and 4ØPSK the output of the QPSK demodulator is applied to the rate 3/4 Viterbi convolutional decoder, then to the ADM codec (The ADM Codec's operation is described in Appendix 5.5). The output of the ADM codec is expanded, amplified, and passed to the channel adapter, which routes the signal to the designated terrestrial interface. When companded FM is used the discriminator's output is deemphasized, expanded, amplified and passed to the channel adapter. The channel adapter routes the signal to the designated terrestrial interface.

During transmission the channel adapter receives the signal from the incoming terrestrial interface and routes the signal to the designated voice channel for transmission. The voice channel is then selected by the frequency synthesizer. The output of the channel adapter is amplified and compressed. When FM companding is used, then the compressor's output is pre-emphasized and frequency modulated.

When ADM is used, the compressor's output is passed to the ADM codec and thence to a rate 3/4 Viterbi convolutional encoder. The IF signals of all the CRT channels are combined, amplified, up converted. amplified and transmitted to the satellite

The channel adapter provides an interface between the telephone exchange and the satellite. The channel adapters can respond to the following instructions:

a.) Satellite channel (trunk) seizure
b.) Satellite channel (trunk) release
c.) Terrestrial channel (trunk) seizure
d.) Terrestrial channel (trunk) release
e.) Supervisory signals
f.) Control signals
g.) Test signals
h.) User's identification codes (user's phone numbers)
i.) System computer commands for the frequency synthesizer
j.) System computer status controls

The channel adapters can provide the following functions:

a.) Dial tone
b.) Busy tone
c.) On recognition of a user's identification code the "handshaking" function can be provided.
d.) Termination of calls, when either party on the line decides to "hang up".
e.) With the aid of the system computer the proper frequency for transmission and reception is selected.

When a call is addressed to a terrestrial (telephone) exchange, the channel adapter looks for an idle terrestrial trunk. When an idle terrestrial telephone trunk is found the channel adapter routes the call from the calling party to the terrestrial telephone exchange. If all the trunks are "busy" the channel adapter initiates a "busy" tone to the calling party.

5. The Communication Management Facility

The Communication Management Facility (CMF) can perform the same operations as the CRT; however, in addition to its regular operations it also performs the required communication management functions for the entire system.

In order to provide a redundant CMF operation, it is assumed that there will be two CMF earth stations for the land mobile satellite communication system.

Each CMF will have a master computer to coordinate all the system supervision control and testing functions. In addition, the CMF will also perform the required bookkeeping and billing for the entire system. The CMF, in conjunction with the individual CRT system computers, periodically checks the status of each CRT. Each and every function of a CRT is tested by the CMF. Upon detection of a failure the corresponding redundant CRT equipment is turned on. Also when a failure is detected by the CMF, a service crew is dispatched to repair the particular failure of a given CRT.

Each and every CRT system computer will have an Automatic Message Accounting System (AMAS). The AMAS provides records for billing and accounting purposes, and also provides traffic statistics records, which allow the CMF to evaluate the performance of each and every CRT in the system. The records of each AMAS is recorded on magnetic tape, which are periodically sent to the CMF. The CMF upon inspection of these magnetic tape contents can generate two kinds of information these are:

a. Preparation of the users' bill. The billing procedure also accounts for the usage of the terrestrial system, (the users' bill, for example, can be automatically prepared on computer cards).

b. The initiation of an expansion action for a congested CRT. (this procedure takes place when congestion is indicated by the analysis of an individual CRT's traffic statistics).

6. The Mobile Radios of the Land Mobile Satellite Communication System

The mobile radios of the land mobile satellite service will possess all of the assets of the present day mobile radios. When frequency synthesizers are used operation in more than one frequency band is possible. For example operation in both the 800 MHz band and the 620 to 790 MHz band can be provided. The use of the 450 to 512 MHz and the 1700 to 1900 MHz bands can also be accomodated in the same fashion. The economic break-even point for the use of a frequency synthesizer versus the use of individual crystals for carrier frequency generation seems to be in the region of 8 to 12 frequencies at the present time. In fact, it has been indicated that the manufacturing plan for the new 1978 800 MHz band mobile radios include provisions for hundreds of carrier frequencies. Projected cost of these new mobile radios will be about the same as the cost of present day mobile radios (which possess only an 8 to 12 carrier frequency capability). This study assumes that the mobile radios of the land mobile satellite system will have a minimum of 48 distinct carrier frequencies, (the requirement for the 48 distinct frequency capability is derived in Appendix 5.4.)

The mobile radios of the satellite land mobile system also include a module to process a pilot reference. This provides a reference frequency for the synthesizer and its level also adjusts the transmitter power so that the satellite or transponder receives the correct power. Thus, except for changes in the frequency synthesizer application, the addition of a pilot reference module, and the possible introduction of a new modulation technique (such as QPSK-ADM) the radio system configuration of the satellite service is the same as that of the present day mobile radios. The pertinent specifications and performance features of the present day mobile radios also are applicable to the radios of the land mobile satellite service

A block diagram of the mobile radio for the land mobile satellite services is shown in Figure 2-17. The received signal is preamplified and down converted. The up and down converters' LO frequencies are controlled by the Pilot Reference System which receives the pilot signal from the Pilot Reference Generator/Processor. The pilot reference signal is transmitted by the CMF via the satellite to all the CRT's and to all the mobile radio users. The downconverter output is an IF carrier signal; when a steerable antenna is used, then the first IF amplifier also provides the AGC signal for the antenna azimuth step tracking equipment, (the step tracker's operation is described in Appendix 5.2).

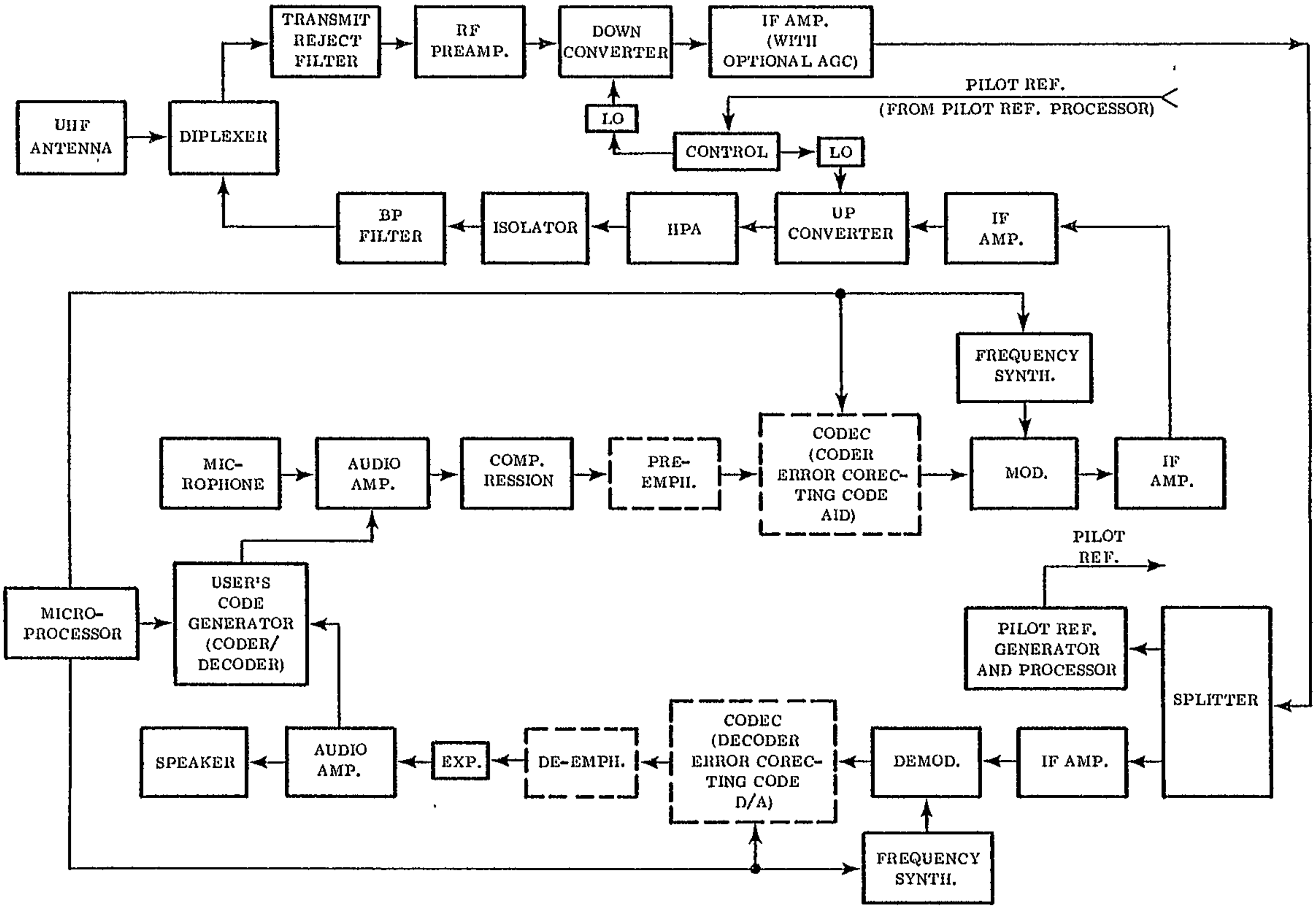

Figure 2-17. The Land Mobile Radio of the Land Mobile Satellite Service

The signal from the first IF amplifier also is applied to the voice signal demodulator, (the demodulator receives a reference carrier from the frequency synthesizer). The frequency synthesizer in conjunction with the microprocessor logic continuously scans at least 48 frequencies. When an incoming speech signal is detected by the systems logic, the scanning stops and both the modulator and the demodulator are set to corresponding frequencies When transmission is requested by the user, the frequency synthesizer (in conjunction with the system logic) sets both the modulator and the demodulator at the first idle frequency pair found during the frequency scanning.

If the modulation is QPSK-ADM type, then a QPSK demodulator is used, followed by a rate 3/4 Viterbi convolutional decoder, and by an ADM coder, which provides the input to the expansion unit. The expansion unit's output is applied to an audio amplifier, and subsequently to a speaker. If the modulation is companded FM, then a discriminator is used followed by a de-emphasis circuit, thence amplified and routed to the speaker.

At the transmit end the microphone audio is amplified and compressed. If an FM-compander is used, the compressor's output is applied to a pre-emphasis circuit. and subsequently to a frequency modulator. If QPSK-ADM modulation is used the signal from the compressor is passed to the ADM coder and thence to the rate 3/4 Viterbi convolutional encoder. The output is QPSK modulated onto an IF carrier, up converted, amplified. filtered and transmitted via the antenna.

7. The Signalling Arrangement of the Land Mobile Satellite Communication Service

The signalling arrangement of the Land Mobile Satellite Communication Service is similar to the signalling arrangement of the Present Multi Access Mobile radio System. In the satellite land mobile system, a free channel is automatically seized and signalling provided only to the destination user.

A seven digit code with area codes and the mobile radio user's a designation code is used. The codes (or phone numbers) are transmitted on the "signalling tones" which can be arranged in the following way·

TONE CODE	FREQUENCY (Hz)	TONE CODE	FREQUENCY (Hz)
R	487	7	1537
1	637	8	1687
2	787	9	1837
3	937	10	1987
4	1087	C	2137
5	1237	M1	2287
6	1387	M2	2437

The M1 and M2 tone codes are used for differentiating a mobile user from a fixed user (These are the mobile radio user's designation codes.) Each tone is used to identify one digit of the mobile radio user's "phone number". Both the user radio and the CRT system computer are programmed with the same identification code. The "R" and the "C" tones provide supervisory and control functions. The signalling from the CRT to the mobile radio user and from the mobile radio user to the CRT are similar to the signalling sequences depicted in Figures 2-13 and 2-14 respectively. In fact, the only difference between the signalling sequences of the satellite land mobile system and the signalling sequences shown in Figures 2-13 and 2-14 is that in the satellite land mobile system a 9 digit tone (7 identification code tones plus 2 user designation tones) are used; while in the signalling schemes of Figure 2-14 and 2-15 only 4 signalling tones are used. Due to this difference, the signalling time is also extended by about 40 milliseconds.

The signalling tones are sequential and are used only during signalling and supervision or control intervals. The speech signal is passed between the CRT and the mobile radio only after the signalling is completed.

When the user radio is not in use, the frequency synthesizer, along with the system logic, continuously scans the assigned radio frequency slots. When an RF carrier is received system logic determines whether or not the user identification code is present. If the user code is not identified, then the mobile radios frequency synthesizer continues to scan. When the user code is identified, the frequency synthesizer stops scan and both the transmitter and receiver are set to corresponding frequencies. The mobile radio automatically sends its code back to the CRT. This "handshaking" is accomplished while the user set is still "idle". At the time of call initiation the CRT is placing a ringing signal on the user frequency. The ringing signals are generated by the "R" and "C" tones. When the user set goes "off hook" (e.g. acknowledges the call) a set of "R" and "C" tones are generated by the user radio back to the CRT which connects the calling party to the user mobile radio set and a call is established.

When the mobile radio user initiates a call, he lifts the handset from the hook; and thereby turns his transmitter on. An idle voice channel for transmission has previously been selected by the frequency synthesizer. When the user radio is turned on, it transmits the user's identification code(and the mobile radio designation code). When the CRT receives the user's call attempt, it sends back the users identification code,

completing the "handshaking procedure". The user radio then sends a "connect" signal, which is accomplished by the use of the "R" and "C" tones. When the CRT receives the user's "R" and "C" tones, it generates an audible tone, which indicates to the user that he is ready to dial. The user dials the same way as he would a regular telephone set. The dialing tones are generated by the microprocessor and the dialing tone generator (See Figure 2-17). After dialing, a "ring back" signal is sent from the CRT and subsequently the parties are connected for their call. When one of the users hangs up a "disconnect" signal is sent by means of the "R" and "C" tones. Thus, the signalling operation of the land mobile satellite communication system is wholly compatible with the signalling operation of the present telephone system.

8. Signal Characteristics

The modulation characteristics of the FM companded system and the 32 kbps ADM system are drived in Appendix 5.1.

The Modulation Characteristics of the FM Companded System

a. Voice channel baseband bandwidth fm = 3.1 kHz.
b. The peak frequency deviation Δf = 7.316 kHz.
c. The allocated satellite channel noise bandwidth, Bn = 25 kHz.
d. The threshold carrier-to-noise ratio is 10 dB.
e. Companding improvement of 8 dB is considered.
f. The pre-emphasis improvement is 6 dB, and the weighting improvement is 2.5 dB.
g. The minimum audio test-tone signal to weighted noise ratio, S/N = 44 dB, and with a 6 dB C/N margin the S/N is 50 dB for at least 80% of the time.
h. The peak modulation index, M = 2.36.

The Modulation Characteristics of the 32 kbps (information bit rate) QPSK-ADM System

a. The required uncoded bandwidth is 19.2 kHz.

b. The required Viterbi rate 3/4 convolutionally coded noise bandwidth is 25.6 kHz. For this mode of operation a 28 kHz bandwidth is assumed.
c. The required rate 7/8 SCPC forward-error corrected coded noise bandwidth is 21.95 kHz. In this study a 25 kHz noise bandwidth is used.
d. The C/N_o requirement for the uncoded case is 54 dB. The C/N used in this study is 13.2 dB, which includes equipment degradation.

e. The rate 3/4 Viterbi convolutionally coded C/N_o is about 50 dB; while the required C/N is 9.2 dB.

f. When the rate 7/8 SCPC channel type FEC is used, then the C/N_o is about 52 dB; while the required C/N is 11.2 dB.

g. The expected performances of all three cases results in a articulation index (A1) of 0.65, which corresponds to a 98% speech intelligibility.

9. Applications of Microprocessors and Digital Codecs

In the past few years, the microprocessor and the digital codec technology has advanced considerably due to the introduction of LSI.

a. Microprocessors

The IEEE Spectrum of the March 1977 issue provides an elaborate survey of microprocessor applications. The examples to follow are from this survey. Microprocessors assist the complicated handshaking procedures required to make a mobile radio call. In the Radyx Incorporated radiotelephone system base-station equipment microprocessors handle many of the required switching functions. In one of the Motorola (Schaumberg Ill.) mobile radio terminals, a microprocessor controls the terminal and displays several lines of alphanumeric information. In the ESL, Incorporated (Sunnyvale, California) mobile station the handshaking also is accomplished by a microprocessor. The Martin Marietta (Orlando, Florida) mobile telephone communication systems microprocessor controls the communications with the nationwide telephone network, including handshaking and decoding of all tones and markers from the base station. The microprocessor based GTE Automatic Electric (Northlake, Illinois) GTD-120 PABX (private automatic branch exchange) can serve up to 120 lines from 28 trunks. The Wescon Incorporated (Downers Grove, Illinois) 580 DSS can serve up to 2400 lines from 600 trunks. The DAMA (demand assigned multiple access) microprocessor based system of Motorola, Incorporated (Scottsdale, Arizona) can take data at 75 to 4800 bps and time division multiplex this data into a satellite communication channel at modulation rates of 9600 to 32,000 bps. Another microprocessor in this system provides buffer storage to absorb clock timing differences, and adds synchronization codes to the error correcting encoder circuits. Microprocessors also are used to perform the error correcting algorithms. Signal processing also can be conveniently performed by microprocessors. Digital filtering associated with A/D and D/A conversions also can be performed by microprocessors.

b. Digital Codecs

In the February 1977 issue of the IEEE Spectrum ("Clipping in Digital Telephone") a number of available digital codecs are described. The significant codec applications from this issue are discussed in this section. Presently the DAC 76 from Precision Monolithics (Santa Clara, California) can perform a μ 255 law companding D/A conversion, (the μ 255 law companding is used in the United States, Canada, Japan and some Latin American Countries). The μ 255 compresses the input signal according to a piecewise-linear approximation of a logarithmic relationship, the μ is a coefficient in the logarithmic expression). This chip is sold for $19.00 in quantities of 100 to 999. Signetics expects to have its ST-100 PCM codec (coder/decoder) available by the first half of 1977. National Semiconductor also plans to have a PCM codec on the market in the near future. Both of these codecs will cost about $10.00 in quantity. The additional filters required at the input and output of the PCM codec will cost about $10.00 in quantities. Motorola also expects to introduce a PCM codec early this year. Harris Semiconductor has announced its HC-55516 and HC-55532 (for 16 and 32 kbps operation) Adaptive Delta Modulation (ADM) codecs. (These codec operations are described in Appendix 5.5) Motorola is also developing its MC3418 ADM codec, which will be aimed at commercial applications. National Semiconductor offers two fifth order elliptic filters for use with their PCM codec. these are the AF130 and the AF131. The cost of these filters in large quantities are about $4.00 to $5.00.

Thus, in the near future beginning with 1978 or 1979) a significant drop in the cost of design, development and manufacturing of switching equipments, SCPC earth stations, mobile radios, and telephone routing systems can be expected through the use of the microprocessors and digital codecs.

2.8 PROPAGATION EFFECTS

A. PROPAGATION EFFECTS AT UHF AND S BANDS

In the UHF frequency range, the atmospheric and tropospheric effects are negligible. Rain attenuation and depolarization effects due to rain also are negligible. Faraday effect, although present, can be compensated by the use of circular polarization. S band is virtually immune to propagation effects.

The propagation effects of significance in the UHF frequency range are

- Man made noise
- Multipath

Man made noise (which is primarily automobile ignition noise) is encountered in urban and suburban environments and the net effect of this on both analog and digital modulation schemes is that larger carrier power has to be provided. To counteract typical suburban noise about 2 to 3 dB of additional margin is considered to provide adequate protection. Operation within an urban environment is not considered in this study.

The multipath phenomenon at UHF has been examined by adequately representing it by a multiscatterer model of reflecting surfaces. Such a model has been structured and variability of resultant received signal has been estimated. The variability is based upon the assumption that the reflected power is 1% of the direct power. Moreover, due to the low gain mobile antenna, no discrimination to multipath signals has been assumed.

In a multipath environment, the received signal consists of the direct-path signal and the multipath signal. Due to the environment, the multipath signal is not a single signal but a multiplicity of signals. The case which is much more representative of actual multipath in an urban environment involves a multiplicity of multipath signals along with the direct path signal incident on the same receiving antenna.

The multipath fading behavior can be appropriately modeled by considering the direct path signal as a constant phasor and each of the large multipath signals as a phasor with uniformly distributed random phase. The multipath signals are allowed unequal amplitude with the resultant vector sum having a rms amplitude "k" which is related to the reflection coefficient. The resultant of the multipath signals will have a Rayleigh distribution and the total signal consisting of the direct signal and various multipath components will be the vector sum of the direct signal and the Rayleigh distributed multipath signal.

The cumulative probability distribution function of the resultant signal R as modeled above has been derived by Rice[4] and is given by the expression

$$P(R \geq \underline{R}) = \frac{2}{k^2} \int_{\underline{R}}^{\infty} R \; I_o \left(\frac{2R}{k^2}\right) \exp\left[- \frac{(1 + R^2)}{k^2} \right] dR$$

where $I_o(\cdot)$ is a Bessel function with imaginary argument and is defined as

$$I_o(Z) = J_o(i Z) = \frac{1}{\pi} \int_0^{\pi} \exp\left[Z \; \text{Cos} \; \Theta \right] d\Theta$$

and $\underline{R}$ is a particular value of R.

The amplitude variability as a function of the cumulative probability with $k = 0.1$ has been plotted in Figure 2-18. In the multipath model if the various multipath signals have the rms amplitudes

$$M_1, M_2 \text{------------------------} M_n$$

then $$k \triangleq \sqrt{M_1^2 + M_2^2 \text{---------} M_n^2}$$

From the plot of the probability distribution function it can be seen that 99% of the time the amplitude variability due to multipath effect is less than 1.5dB when $k = 0.1$. Under these conditions, a margin of 6 dB should be very adequate to protect against man made noise and multipath propagation effects. For larger values of k which will hold in areas that are more reflective, the fades will be deeper. Under such conditions larger margins will be required.

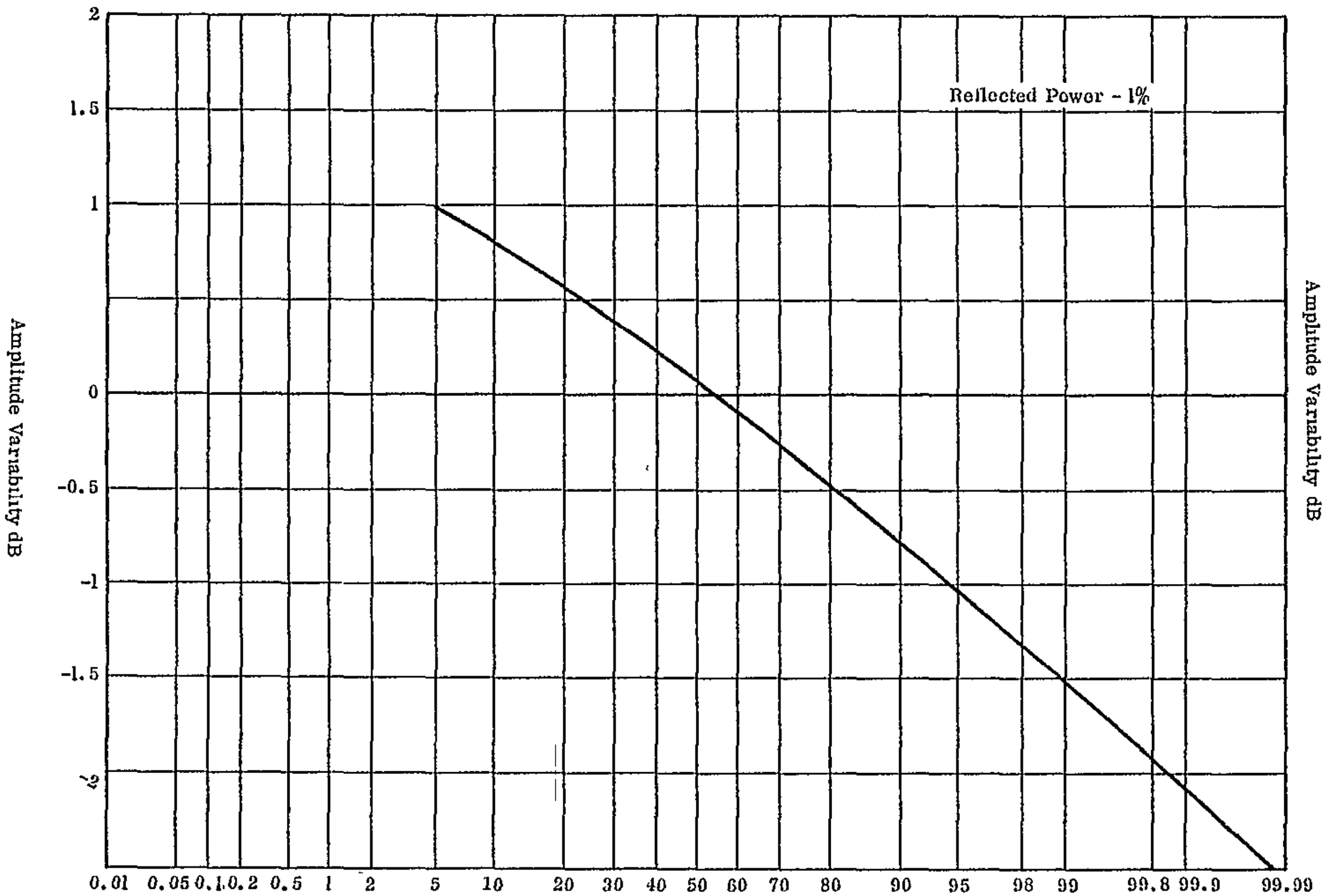

Figure 2-18. Probability That Variability is Less Than Ordinate

B. K-BAND PROPAGATION EFFECTS

The RF attenuation statistics at Ku band due to rain have been included in the study. Rain is the only climatic condition which has a significant effect.* Since the climatic conditions and the rain activity varies significantly within the geographical boundries of the U. S., local attenuation statistics must be considered. Models which consist of the cumulative distribution functions of rain induced RF attenuation have been constructed for NE, SE, Central and Western regions of U. S. which are described in Appendix 3, Volume 2. Since the RF attenuation depends upon rain rate, the cumulative distribution functions of attenuation are developed using average rain rate data and techniques for converting this data to RF attenuation. Significant factors which influence the conversion and the methodology of conversion are explained in Appendix 3; the rain rate data has also been given there. Furthermore, in Appendix-3 it is demonstrated that these models are supported by data collected from experiments conducted by NASA and Comsat on ATS-6. The models constructed for the four geographical divisions of U. S. coupled with NASA measurements data for other selected geographical regions such as Alaska, Hawaii etc. are used in the study. Typical results derived from this data and models are given in Table 2-3.

In the study, margin is provided in the links to take care of rain attenuation such that outage does not exceed 0.1%. Additionally, in the case of the interactive services, the margin has been sized to include the impact of rain induced increases in receive system noise temperature. A nominal 200 ^{o}K clear sky receive system termperature has been used in deriving these margin increases. In the case of the broadcast services, the receive system noise temperatures are much higher. Consequently, rain induced noise is of minor importance and the link margins are sized to reflect attenuation alone. Where the margin necessary to meet the outage requirement is large, methods have been discussed to ameliorate the impact and such methods have been used where necessary in the study. For example, rain attenuation in the Gulf of Mexico and Florida regions is high, and in the study the satellite models direct more energy to these regions. Other possible methods are discussed in Appendix.3. Attenuation margin as a function of outage is also given in Appendix 3.

*Depolarization due to rain is ignored because dual polarized Ku band systems are not considered in the services.

Table 2-3. Typical Rain Attenuation Effects

Geographical Region	Rain Attenuation and Equivalent Sky Noise for 0.1% outage at GHz	
	Rain Attenuation (dB)	Equivalent Sky Noise[(1)] (Tsky) $^{\circ}K$
NE	4	164
SE	10	246
Central	4	164
West	1	56
Alaska	8	230

Note: (1) $Tsky = \frac{\alpha - 1}{\alpha} \; 273^{\circ}K$, where α = attenuation

3 0 TRADEOFFS, INTERACTIVE SERVICES

3.1 INTRODUCTION

A. OVERVIEW OF RESULTS

Five special transmit/receive communications services, four operating at Ku-band and one at UHF, have been subjected to tradeoff evaluations, as a function of a wide variety of system options, to develop optimized satellite/ground terminal configurations and annual cost to the user. The services are special in that they are not presently being supplied on a major scale by the communications carriers. They are also somewhat unique in that small earth terminal technology is employed to provide direct, flexible, long distance user to user interconnections. The five services and representative samples of the tradeoff results are depicted in Table 3-1. The mobile radio service is the one operating at UHF.

The table's results are based on the specific operating scenarios associated with each service. The "Point-to-Point (i. e. two way) TV" service has been configured to supply medical diagnostic interconnections between multiple rural hospitals-medical technicians and urban-university specialist. The "Compressed Bandwidth TV/Facsimile" service provides teleconferencing to the government, industry, the medical professions, and educators. A transportable terminal brings the facilities to the customer's location and charges are levied on a per call basis. The "Voice/Facsimile" service gives another level of teleconferencing capability at a far lower cost. The user owns or leases his own terminal which can handle independent voice, facsimile and data transmissions as well as teleconferencing. Both FDMA and TDMA approaches to system implementation are considered. All other services are configured in an FDMA mode alone. The "Multi-channel Voice/Data" service supplies dedicated thin route trunking between users. Eleven voice channels plus a 64 Kbps data capability is provided. The "Mobile Radio" service provides telephone service to mobile users (e. g. trucks, trains, cars, law enforcement vehicles, etc.). Both mobile/mobile and mobile/fixed interactions can be handled. Connections to fixed users are made by accessing the conventional telephone system.

The basic system configurations, displayed in Table 3-1, were chosen to be representative of the small terminal networks that might reasonably be implemented before 1985. The satellite and earth station configurations and costs for a wider range of networks sizes and launch vehicles are displayed in Section 3. 3. As shown by the table, it is expected that the requirements for terminals supplying wideband services will be in the hundreds while the need for narrowband service terminals may be in the ten to one hundred thousands range.

The average number of terminals/satellite signal "slot" is a major factor in determining the annual costs per user and the most cost effective tradeoff between satellite and earth terminal requirements. A large number of terminals/slot reduces the cost allocation for satellite power and reduces the annual cost per user. It also allows a cost effective increase in satellite power and corresponding decrease in earth terminal requirements. The values for this parameter, indicated in Table 3-1, are fixed for all

Table 3-1 Summary Optimized System Annual Cost/Configuration

	System Config.			Gn'd Term Config.			Sat. Config.			Average System Cost/Term (2)				
Service	Total Term	No. Term/ Sat. Sig. Slot	Launch Vehicle	Ant Dia.	Recvr. Temp.	Xmitter Pwr.	No. Beams	Pwr/ Transponder	No. Sigs. Transponder	Total Annual	Per Call	% Due to Sat.	Term	Fixed
Point-to Point TV	10^2	25	Shuttle A/C	9.9 (meters)	100 (^oK)	25 (watts)	4	2.2 (watts)	1	$51.K	$360	44	27	29
Compressed BW TV/ FAX	10^2	4	Shuttle A/C	9.9 (meters)	100 (^oK)	15 (watts)	1	2.5 (watts)	3	$141.2K	$495	34	11	55
Voice/ FAX (FDMA)	10^4	17	Shuttle A/C	4.4 (meters)	260 (^oK)	5 (watts)	1	75 (watts)	112	$9.5K	$90	18	40	42
Multichannel Voice Data	10^2	2	Dedicated Shuttle	7.0 (meters)	265 (^oK)	2 (watts)	4	1.8 (watts)	16	$38.8K	$3	59	26	15
Voice/FAX (TDMA)	10^4	17	Shuttle A/C	3.5 (meters)	450 (^oK)	1 (watts)	4	60 (watts)	295	$22.5K	$215	2.5	9.5	88
Mobile Radio	10^5	50	Dedicated Shuttle (1)	Crossed Dipole/ Folded Monopole	300 (^oK)	2 (watts)	6	1.8 (kilowatts)	1065	$1.1K	$2(3)	25	40	35

Notes: (1) A 60 foot antenna is used on the satellite

(2) Cost for one terminal and one satellite access. This is the total cost of the Point-to-Point TV service where many rural terminals interact with one central terminal in a half duplex mode. In all other cases, it is half of the total since full duplex one-to-one interactions are supplied.

(3) Cost based on each terminal handling an average of 2 calls per day, five days per week. See Section 3-3 for the basis of the other per call cost estimates

system options evaluated. They range from one terminal per slot, for a fixed trunking service, to 17 to 50 terminals per slot for low duty cycle terminals owned or leased by the individual user. An intermediate value of about 4 or 5 is applicable to high duty cycle terminals made available to a number of users (e.g. by employing transportable terminals).

Typical launch vehicles, for the satellites serving networks of the size indicated in the table, will be in the Atlas Centaur and Dedicated Shuttle classes. Big satellites give an economy of scale that reduces the annual costs per user. Further, the magnitude of the total load depicted is compatible with the big satellites. The mobile radio service alone requires the total capability of a Dedicated Shuttle size satellite. The other services individually require from 8% to 40% of the total RF power available on an Atlas Centaur satellite and the composite load of the four is about 70%. If a Dedicated Shuttle is employed, the loading is about half as large (i.e. less than 35% composite load) and a considerable capability remains.

The ground terminals, displayed in the table, provide Ku-band antennas having diameters ranging from about 3.5 meters to 9.9 meters. Antennas up to 4.5 meters have a manual steering capability while larger antennas are autotracked. Ku-band receivers range from cryogenically cooled paramps (i.e. 30°K to 120°K devices) to GaAs FET low noise receivers (i.e. 300°K to 950°K devices). At intermediate device temperatures (i.e. 120°K to 300°K), uncooled paramps are used. These receive system temperatures are clear sky values. Rain increases Ku-band system noise temperatures Sufficient margin has been provided to insure link outages due to rain of $\approx 0.20\%$ The UHF receiver is a bipolar transistor. Transmitters are all at relatively low powers ranging from about 1 to 2 watt solid state GaAs FET devices up to 25 watt TWTAs. The UHF transmitter is a transistor amplifier. The Ku-band requirements can be reduced somewhat by allowing a modest increase in system costs. G/T reductions of 2 5 dB to 4.5 dB result in cost increases of only 10%. This results in antenna diameters ranging from 3 meters to 9 meters, receiver temperatures ranging from 230°K to 745°K, and transmitter powers ranging from 1.5 watts to 45 watts. Some further reduction in both terminal G/T and EIRP can be realized if the satellite antenna is not configured to provide extra gain into the high rain outage areas (i.e. the Southeastern United States) at the expense of reduced gain into other areas of the country (See Section 3.3.A.4). This gain reduction amounts to about 3.5 dB for 4 beam satellites and is negligible for one beam satellites. Thus, the maximum requirements, for four beam satellite terminals, can be reduced to a 7 meter antenna and a GaAs FET (i.e. 350°K) receiver. With or without this last reduction, the results show that the use of a multibeam satellite antenna results in reduced ground terminal requirements.

The Ku-band satellites, displayed in the table, provide either one beam U.S. coverage or four beam time zone coverage antennas together with modest transponder RF power requirements. The UHF satellite is another story. Multiple beams are needed to increase the available bandwidth, through frequency reuse, and increase satellite EIRP to low performance UHF mobile receivers. The latter also requires high transponder power. The satellite, configured to meet these requirements, employs a solar array having a higher sunlight to DC power conversion efficiency than those provided on current spacecraft.

The Ku-band results indicate that time zone antennas can be effectively used to reduce system costs in selected applications. These being FDMA systems where the traffic requirements are regionalized and TDMA systems involving high levels of traffic volume per terminal (e.g. $\geq$ 1 Mbps). In an FDMA system designed for U.S. wide interactions, the beam to beam cross strapping channelization required increases the routing filters as the square of the number of beams. Further, the inflexibility of the channelization means that it must be oversized to effectively handle demand assignment traffic. Consequently, the four beam approach has been considered applicable only to cases where the user interconnectivity requirements can be regionalized (i.e. Point-to-Point TV), or the user requirements are semi-regionalized and fixed and predictable in advance (i.e. Multichannel Voice/Data). Note that TDMA has the potential of overcoming all the disadvantages of an FDMA approach to multibeam systems. However, the high cost of TDMA modems makes such a system cost effective only when the data rate per terminal is high.

The optimum transponder power level is found to be an important parameter in the optimum cost per user. Power levels below about 10 watts represent inefficient satellite designs which inflate user costs. At these power levels, the weight of channelization hardware exceeds that of the RF power amplifier. As seen in the table, the results for the Point-to-Point TV, Compressed Bandwidth TV/Facsimile, and Multichannel Voice/Data all fall into this category. The most effective means for increasing transponder power is to increase the number of signals sharing an individual transponder. This implies widening the satellite transponder bandwidth. Variations in the bandwidth are used in this study as a means for varying the number of signals sharing a transponder. A 36 MHz upper bound, consistent with present INTELSAT and DOMSAT channelizations was assumed. Further, even when narrower band channelizations are considered, the use of the 36 MHz transponders is not precluded. However, the trends indicate bandwidths wider than 36 MHz should be considered for at least the three services listed above.

The costs, displayed in Table 3-1, appear to be reasonable except for those associated with the "Compressed Bandwidth TV/Facsimile" and "Voice/Facsimile" (TDMA) services. These amount to \$990 for a full duplex 1-1/2 hour video conference and \$430 for a full duplex 1 hour audio conference. Teleconferencing must be compared with typical U.S. Business expenses of about \$300 to \$500 per person for a face to face conference. As indicated by the table, the high costs are primarily the result of the fixed performance items (e.g. IF/baseband equipment, control/test equipment, packaging, shelters, environmental control equipment, operating expense, etc.). In the case of the video service, it is operator costs associated with the cameras and transportable terminal that are unreasonable. In the case of the audio service, it is the TDMA modems that drive the overall costs out of reach. In the other services, satellite costs dominate if a wideband capability (i.e. 700 Kbps) is needed while ground terminal costs dominate the narrowband (i.e. 150 Kbps) configurations. Various innovations and revisions, to the Ku-band service configurations modeled herein, which may decrease costs, are summarized in Table 3-2.

Table 3-2 Potential Cost Reducing Factors/Innovations

SERVICE	FACTORS/INNOVATIONS
Point-to-Point TV	(1) Multibeam (e. g. 8-16) FDMA sat., (2) Longer life/higher reliability sat., (3) Shuttle optimized sat., (4) Improved sat. technology (i. e. higher efficiency solar arrays, ion jets, etc.,) (5) Video camera performance/cost trade-offs, (6) Audio only return link to remote hospitals, and, (7) More sigs,/sat. chan. (i. e. wider bandwidth transponders).
Compressed Bandwidth TV/Facsimile	(1) Multibeam synchronized TDMA* sat. system, (2) Items (2), (3) and (4) above, (3) Conferences durations reduced to an average of an hour, (4) Lower data rate TV (e.g. 1.5 Mbps), (5) Combined teleconferencing/fax./data services with terminals owned by individual users and (6) More sigs./sat. chan. (i. e. wider bandwidth)
Voice/Facsimile (FDMA)	(1) Error correction coding/decoding, (2) Lower operating frequency (e.g. C-band or S-band), and (3) High volume procurement/implementation (e. g. 10^5 units)
Multichannel Voice/Data	(1) Items (2), (3) and (4) under Point-to-Point TV, (2) Multibeam FDMA or synchronized TDMA sat. (3) High volume procurement/implementation, (4) Delta modulation for voice channel A/D, and (5) More sigs./sat. chan. (i. e. wider bandwidth)

* Beam switching in the satellite is synchronized to the TDMA frame format.

The variation of average annual cost per user as a function of the link outage requirement is examined for all Ku-band services with identical results. An almost negligible cost increase occurs as the acceptable link outage decreases from 1% to about 0.25%. Cost increases become significant at an outage of about 0.075%. Costs are totally unreasonable at an outage of 0.01%.

The means for handling the differences in Ku-band rain attenuations across the country also are examined. It is concluded that an equal distribution of antenna gains and identical ground terminals can be used across the country for link outages >0.5%. As outage requirements are reduced further to about 0.075%, unequal satellite antenna gains can be effectively employed. At still lower outages, the satellite antenna gain offsets need to be compensated by variations in the ground terminal performance requirements. Finally, to provide a system outage of 0.01%, it may be necessary to accept a slightly poorer outage in the Southeastern U.S.

B. SCOPE OF THE SYSTEM OPTIMIZATIONS COMPLETED

The basic system options, considered in the tradeoff, are the satellite, launch vehicle, the probability of link outage, the number of users in a nationwide U.S. network, the number of beams on the satellite and the number of user signals accessing a satellite channel. The range of variation for each parameter is defined in Table 3-3 for the Ku-band services. All possible permutations of the listed parameters are selected and satellite and ground terminal optimizations completed to determine the minimum cost and corresponding satellite transmitter and ground antenna, receiver, and transmitter requirements. This amounted to thousands of system optimizations requiring the use of a computer.

In the case of the land mobile service, the range of options is more limited and manual tradeoffs could be performed. Link outage is not a consideration (i.e. a fixed link margin is provided) and the number of user signals per satellite transponder is a dependent variable determined by the selection of the launch vehicle, number of beams per satellite, and the number of user terminals in the network. The Shuttle A/C launch vehicle together with 2, 6, and 25 beam antennas plus the Dedicated Shuttle with 2, 6, 25 and 77 beam antennas are considered. In each option, the user network is allowed to vary in small increments from 10,000 to the maximum supportable. UHF bandwidth is the constraining item determining the maximum number of users supportable. It is increased through greater frequency reuse as the number of satellite antenna beams become larger; use of dual polarization also increases the bandwidth. Up to 320,000 users can be efficiently served by two beam satellites, 480,000 by six beam satellites, 2,000,000 by 25 beam satellites, and 6,000,000 by the 77 beam satellites.

Table 3-3 Basic Ku-Band System Options Subjected to Satellite/Ground Complex Tradeoffs

Service	Options Considered				
	Launch Vehicle	Link Outage	Number of Terminals	Number of Sat. Beams	No. of User Sigs/Sat Chan.
Point-to-Point TV	Delta 2914 Delta 3914 Atlas Centaur Shuttle 3914 (1) Shuttle A/C (2) Dedicated Shut.	1% 0.25% 0.1% 0.075% 0.05% 0.025% 0.01%	10 10^2 10^3	1 4	1
Compressed Band width TV/Fac-simile	Same as above	Same as above	Same as above	Same as above	1 2 3
Voice/Facsimile (FDMA)	Same as above	Same as above	10^2 10^3 10^4 10^5	Same as above	14 56 112 224
Voice/Facsimile (TDMA)	Same as above	Same as above	10^2 10^3 10^4	Same as above	295 442
Multichannel Voice/Data	Same as above	Same as above	10 10^2 10^3	Same as above	1 2 8 16

Notes: (1) A Delta 3914 equivalent payload launched on a shuttle vehicle.
(2) An Atlas centaur equivalent payload launched on a shuttle vehicle.

C. OPTIMIZATION APPROACH AND SECTION ORGANIZATION

The Ku-Band system optimizations are accomplished in a series of three major computerized routines. These are: (1) the satellite cost/transponder versus power/transponder (2) the ground terminal cost versus EIRP and G/T, and (3) the average annual cost per user versus satellite and ground terminal performance. After the system options are selected, the output curves from the first two routines are read into the last to allow the satellite vs ground terminal tradeoffs to be completed. This routine employs uplink and downlink performance equations to relate the capabilities of the space and ground segments to the system requirements and options selected. While these equations are being satisfied, the allocated satellite cost per user and the average ground terminal costs are totaled. A systematic search, over a reasonable range of satellite and earth terminal capabilities, is conducted and the lowest cost system configuration selected as optimum. The routine handles variations in ground terminal requirements over four major sectors of the country (i.e. the Northeast, Southeast, West and Midwest). Its outputs for the optimum configuration include: average annual cost per user, satellite power, number of satellite transponders required, percent of satellite consumed, and earth terminal EIRP, G/T, receiver, transmitter and antenna required in each area of the country. Fixed item costs are manually added to satellite and ground terminal costs. The routine is explained in detail in Section 3.4.

The Ku-band earth terminal routine employs the antenna, transmitter and receiver costs versus performance curves, described in Section 3.6, to generate the optimized ground terminal cost versus performance curves. The cost of antenna, receiver and transmitter combinations satisfying EIRP and G/T requirements are totaled. A systematic search, over a reasonable range of subsystem capabilities is conducted and the lowest cost combination selected as the optimum. This routine can provide optimizations for both redundant and nonredundant versions of the transmitter and receiver, and is described in detail in Section 3.5.

The Ku-band satellite routine provides a method for subdividing spacecraft RF power capability and cost such that a cost/performance curve can be generated. It is not an optimization since nothing is traded off. A communications payload capability is allocated (nominally 40%) from the total available geosynchronous orbit payload capability of a given launch vehicle. A channelized communications transponder model is adopted. The weight of the antenna, various transponder components (e.g. receiver, frequency converter, channelization filter, and transmitter), and the transponder prime power source is developed. The annual cost of the total space segment is established, including an active satellite, an in orbit spare, a ground spare, two launch vehicles, launch/orbit insurance, and various other operating costs. The computer starts with one transponder

and increments the number of transponders to vary transponder power downward. At each increment, the transmitter weight and power compatible with the available weight allocation is determined and the space segment costs are suballocated to each transponder. This process proceeds from a single transponder maximum power configuration until the power per transponder is less than one watt. Up to six different launch vehicles are handled in the model. Both one beam and four beam satellites can be configured. The model is explained in greater detail in Section 3.7.

The UHF Mobile Radio optimizations are similar to those indicated above but can be performed manually since the range of the system parameters and options are less. A limited range of ground antennas (i.e. 7 antennas having gains ranging from -5 dB to 17 dB) and a fixed transmitter simplify the ground terminal tradeoffs. Several satellite configurations are considered but the power and cost per channel are not varied. The entire capacity of the satellite is consumed in all cases. The tradeoff with the ground complex is accomplished by varying the bandwidth provided by each satellite. Decreasing the bandwidth from the maximum feasible decreases the number of users possible. This increases the satellite power per user and allocated user cost in a linear fashion and affords a trade-off with the mobile receiver's G/T and cost. In this service, overall operating and fixed equipment costs increase modestly as the size of the network increases. These costs are also computed manually and added on to the satellite and ground complex costs. They are a significant portion of the overall costs. They decrease on a per user basis as the size of the network increases. As a result, they are a strong factor in making large networks cost effective.

The output of these optimizations is summarized and analyzed at length in Sections 3.2 and 3.3. Section 3.2 examines cost variations as a function of Ku-band link outage. The results are quite similar for all services eliminating the need for a detailed service by service evaluation. The remaining results are evaluated service by service in Section 3.3. The format, for Ku-band services, involves considering in order: (1) annual cost versus satellite transponder bandwidth; (2) annual cost versus number of beams per satellite. (3) satellite requirements, (4) satellite and ground terminal cost versus network size, (5) ground terminal requirements, and (6) total system cost breakdown. In the "Point-to-Point TV" service, cost versus satellite transponder bandwidth is not a consideration. In the UHF "Mobile Radio" service, the format is unique since the approach to the tradeoffs and evaluations is unique.

3.2 AVERAGE ANNUAL COST VS PERCENT Ku-BAND LINK OUTAGE

A. RESULTS

After examining a wide variety of transmit/receive services, the major conclusions are:

- The trend in system cost as a function of link outage is quite similar regardless of the system configuration.

- Average annual satellite/ground terminal costs experience a negligible increase as the link outage requirement decreases from 1% to about 0.25% and increases do not become important until the outage is reduced to less than 0.1%.
- Cost increases become unreasonable at a link outage of 0.01%.

The full set of link outage versus cost curves are displayed in Appendix 4. Representative examples are shown in Figures 3-1, -2 and -3. As illustrated, there is a sharp threshold in the cost trend at a link outage of about 0.1% Average annual cost, as used above and in the figures, represents the annual cost per terminal for the satellite plus one fourth of the sum of the annual cost of the ground terminals needed in the Southeast, Northeast, Central and West sections of the U.S. Thus, it is ground terminal costs that are averaged based on an equal distribution of ground terminals across the country. The system design has been structured to equalize the outages per area even though the rain attenuations and required margins differ markedly. This is accomplished by providing 7 dB of extra satellite antenna gain in the direction of the Southeast and by choosing ground terminals of differing EIRP and G/T performance capabilities per area.

B. BACKGROUND OF COST VERSUS LINK OUTAGE RESULTS

Factors having an impact on the cost as a function of link outage include:

- The rain attenuation data employed to develop link margin versus outage requirements.
- Minimum margins established to ensure adequate clear sky performance.
- Differences in minimum margins between digital and analog services.
- Impact of rain attenuation on receiver noise temperature.
- Margin variations from one area of the country to another.
- The approach to allocating the overall outage requirement between the uplink and downlink.

The Ku-Band rain attenuation data employed is summarized in Section 2.5 and discussed in depth in Appendix 3. Separate attenuation curves are defined for each area of the country at 14 GHz and 12 GHz. The data is generated by a link model based on recent data collected by NASA in an ATS-6 experiment. A model was necessary since actual data is not available for all areas and ground antenna elevation angles of interest. The model uses U.S. Weather Bureau rain rate data to make attenuation predictions. The model is confirmed by actual link attenuation measurements made on a satellite located at about 95^{o} west longitude. This location gives relatively high

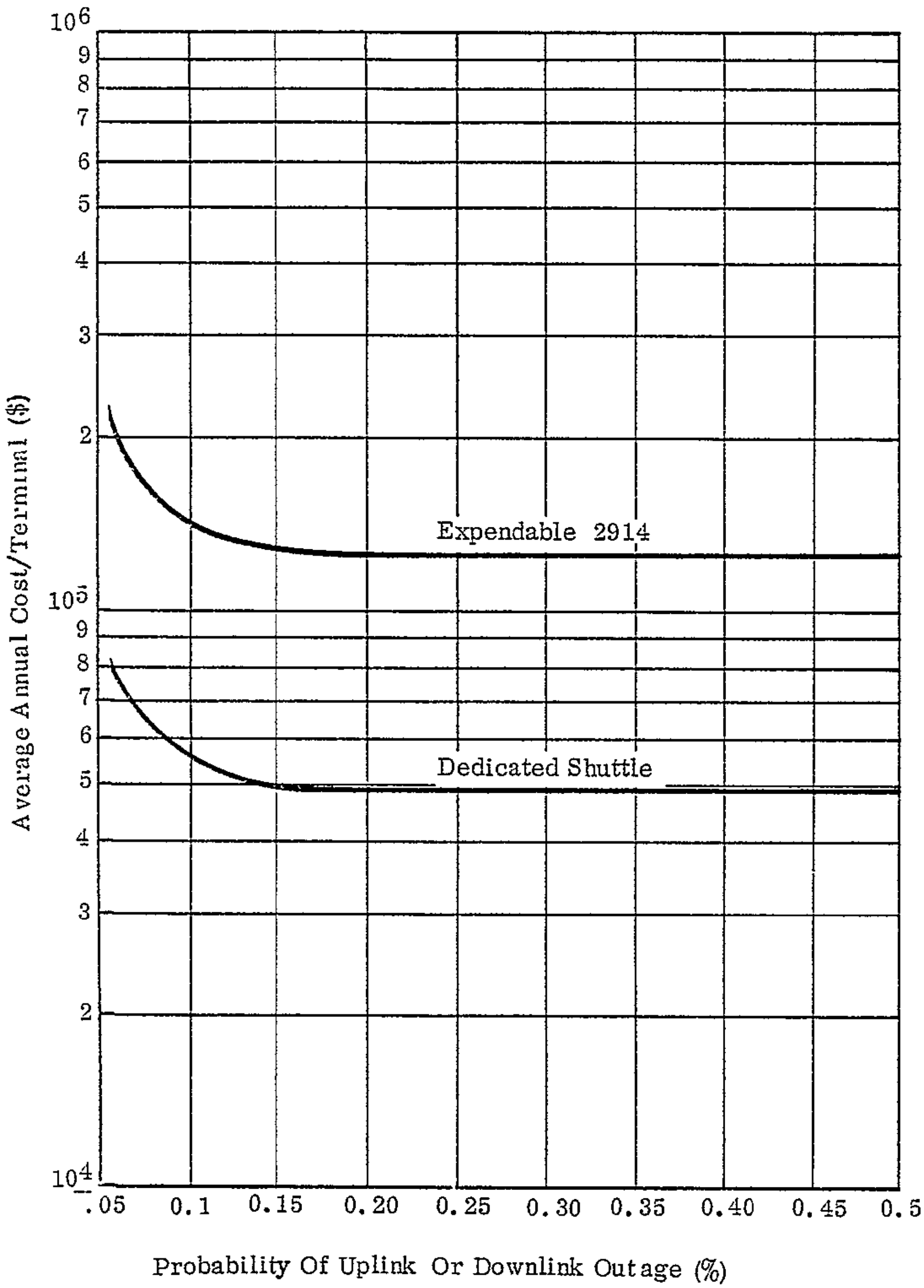

Figure 3-1. Annual Cost vs. Ku-Band Link Outage (1 Beam Satellite, 36 MHz Bandwidth, 100 Terminals) (Compressed Bandwidth TV/Facsimile)

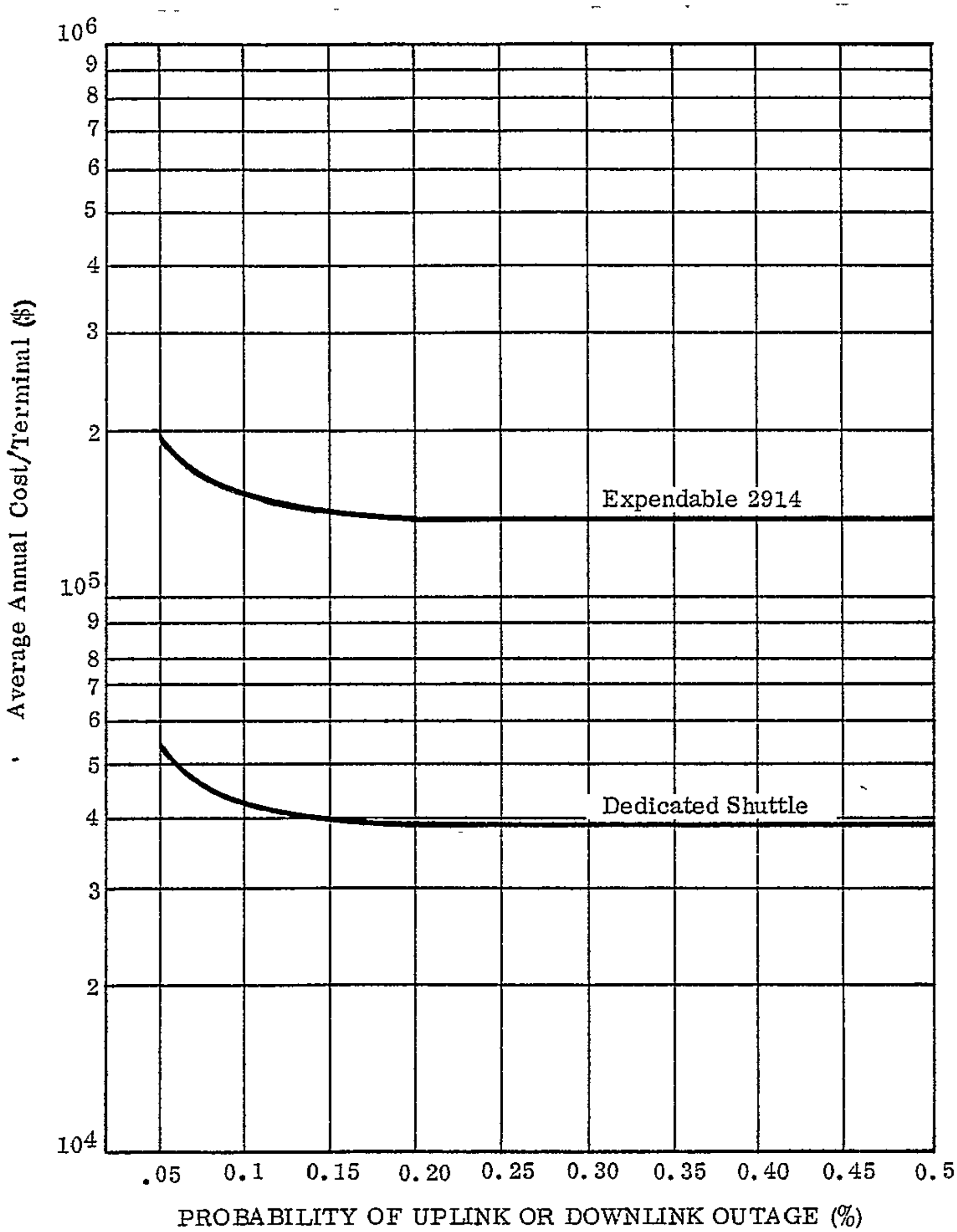

Figure 3-2. Annual Cost vs. Ku-Band Lirk Outage (4 Beam Satellite, 36 MHz Bandwidth , 100 Terminals) (Compressed Bandwidth TV/Facsimile)

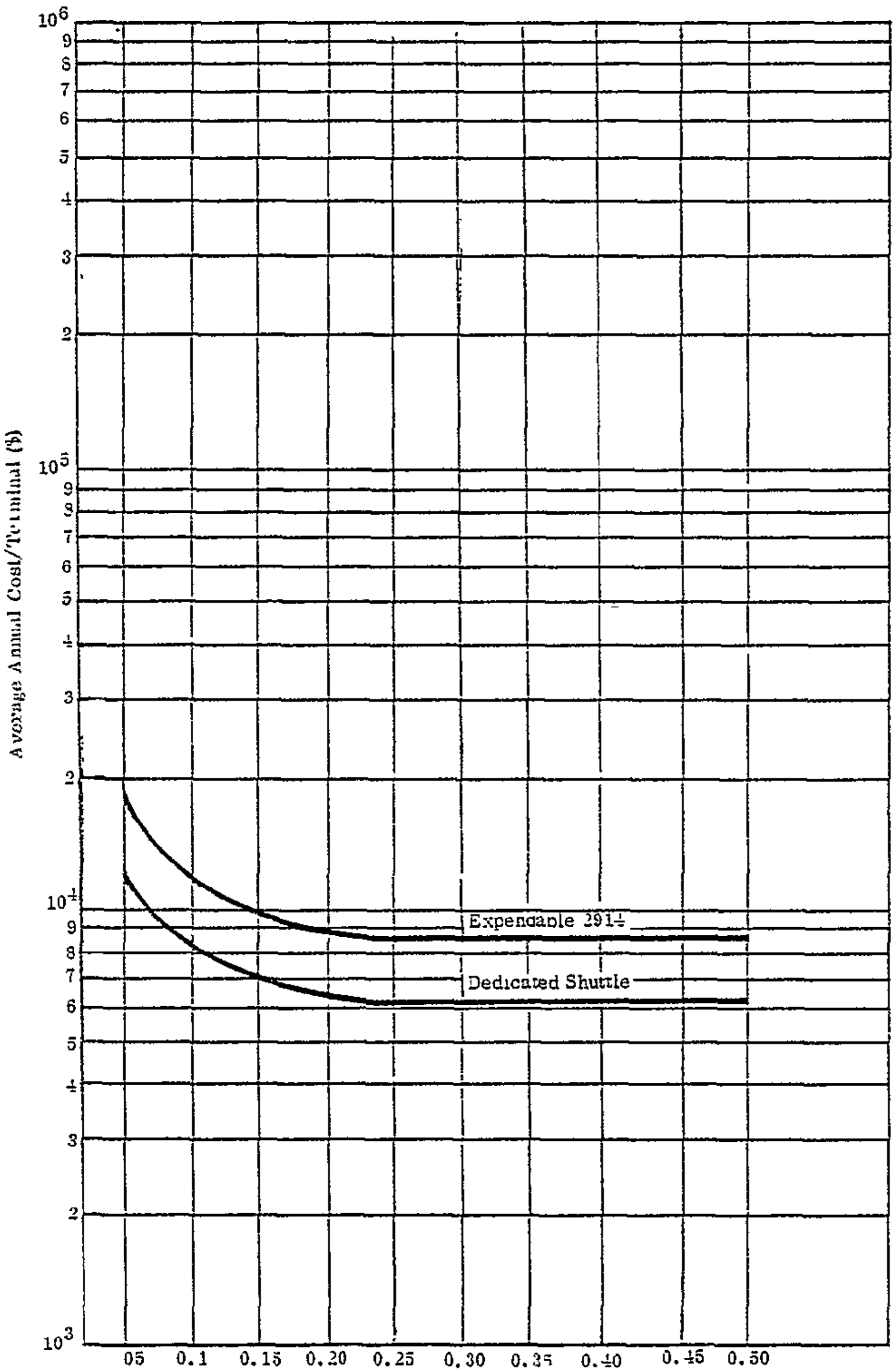

Figure 3-3. Average Annual Cost Vs. Ku-Band Link Outage
(1 Beam, 10^3 Term., 15.68 MHz Bandwidth)
(Voice /Facsimile)

elevation angles for terminals in the eastern U. S. However, the satellite location assumed in this study is 124° west longitude giving low elevation angles for terminals in the eastern U S These elevation angles plus high rain rates made the attenuations for the northeast and southeast quite high. As a result, the average cost obtained for low outages is high. The attenuations in the east are fairly high in almost all projections currently being made Consequently, it is believed the conclusions stated above are valid even though the exact magnitude of the average costs for low link outages is a matter of conjecture

The specific margins, used in the computerized system optimizations, are displayed in Section 3. 4. D. These margins are given as a function of link outage. They include a minimum margin as well as the margin required to combat rain attenuation. The minimum margin ensures high performance during clear sky conditions. The rain margin ensures a minimum acceptable performance level in situations where propagation attenuation is a factor. The rationale employed in developing the minimum margins is explained in detail in Section 3. 4. D. These margins are a major contributor to the flatness of the cost curves as the link outage varies from 1% to 0. 25%. Degraded equipment performance due to failures, aging, changing temperatures and frequency instabilities are also included in the link margin.

As indicated in Section 3. 4. D, different minimum margins are applied to digital and analog services because the difference between minimum performance and high performance is less in the case of the digital services. It should also be noted that the C/N_o values stated for the digital services include 2. 5 dB of modem loss relative to theoretical performance. Thus, while the minimum listed margins are 7 dB for the analog services and 4 dB for digital services, the total effective minimums for the two are 7 dB and 6. 5 dB. A comparison of the average cost versus outage data for digital and analog services reveals no major differences in the cost trend.

Rain attenuation also produces changes in the effective receive system noise temperature. This change is additive. Therefore, its impact is a function of the clear sky receive system noise temperature. The results presented in this study have been adjusted to account for the noise temperature increases in a 250°K receive system. When link outages less than 0. 25% and receivers of a differing performance are considered modest adjustments in the data are appropriate. At link outages of 0. 25% or greater the minimum margins are sufficient to equalize the results.

The average annual cost data encompasses a considerable variation in costs per user from one area of the country to the other. This is due to propagation variations and the added satellite antenna gain to the Southeast. At outages $\leq 0.1\%$, the Southeast is the highest cost area followed by the Northeast, West and Central areas. This trend is a direct result of the propagation phenomena. For outages between 0. 1%

and 0.25% there is little cost deviation from area to area In this range, the extra satellite gain compensates for the high propagation degradation into the Southeast. For outages greater than 0.25%, the Southeast was the lowest cost area while the other areas were equal in cost. In this case, the minimum margin is being applied in all areas and the extra satellite antenna gain into the Southeast produces low cost ground stations

Finally, the average annual cost data presented is based on providing equal outages and corresponding margins on both the satellite uplink and downlink. It is given in terms of the outage experienced on either of these links. An upper bound on the total link outage, P_{TO}, can be obtained from:

$$P_{TO} < \left[1 - (1 - P_u)(1 - P_d)\right]$$

where:

- P_u is the probability of uplink outage, and
- P_d is the probability of downlink outage

a lower bound is approximated by:

$$P_{TO} > P_u P_d + (1-P_u) P_d = P_d$$

since the uplink causes only a minor degradation in overall link performance in all cases (see Section 3.3). As a result, at a link outage 0f 0.1%, as shown in Figures 3-1, -2 and -3, the overall link outage is between 0.1% and 0.2%. A calculation of the exact outage requires a precise knowledge of the margin and attenuation probability distributions on both the uplink and downlink.

The precise allocation of margin and outage requirements between the uplink and downlink is a matter that bears further consideration. It is not expected that major cost improvements (over those developed here based on equal allocations) will be found. However, it is cost-effective to overdesign the uplink when the margins are equal (see Section 3.3). It may also be of some benefit to overdesign the uplink margin and outage allocation.

3.3 SYSTEM PERFORMANCE/COST TRADEOFFS

A. POINT-TO-POINT TV

1. Average Annual Cost Versus Number of Beams Per Satellite

The potential advantage of time zone coverage (i.e., four beam) versus U.S. coverage lies in the additional antenna gain provided. The extent to which this can be turned into a cost-advantage for the Point-to-Point TV service is depicted in Table 3-4. As shown, the cost improvement ranges from about 6% for a Delta 2914 launched satellite to 31% for a Dedicated Shuttle launched satellite. The reduced improvement for the Delta 2914 satellite occurs because of the inefficiencies introduced into the satellite design by the four-beam approach, e.g. three additional wideband receivers and antenna feeds making a total of four. The resultant weight penalty is much more severe on small satellites.

The indicated cost improvements demonstrate the attractiveness of multibeam designs implemented at the higher frequencies (e.g., Ku-Band). The antenna weight penalty is sufficiently small so that it becomes reasonable to oversize the reflector and use multiple feeds to contour composite beams to fit the coverage desired. For example, the approach used in designing the above four-beam antenna, is to oversize the reflector such that eight beams are needed to give U.S. coverage. The eight feeds are then summed in pairs to give four beams. The resultant gain improvement, relative to a U.S. coverage beam, is about 5.5 dB. In addition this gives the flexibility to provide an unequal distribution of gain. If a circular antenna has been used, sized to provide only four beams, the gain advantage would have been only about 3 dB.

One assumption important to the results shown in Table 3-4, is that the user-to-user interconnectivity requirements are regionalized by considering a medical diagnostic service with a number of remote rural hospitals/health care units (e.g., 24) interacting with a team of highly knowledgeable specialists at a big city or university affiliated hospital. Such nets can easily be structured on a time zone basis. If this were structured as a teleconferencing service, where low duty cycle connections are required all across the country. four-beam FDMA operation would not be nearly so attractive.

For example, consider a network of 100 teleconferencing terminals interconnected nationwide. Further, assume that an average of 25 terminals can be handled by each transponder in the satellite. If U.S. coverage is considered four satellite channels are adequate and all terminals have ready access to all satellite channels. On the other hand, in a four-beam design, 16 channels are required. Each of the four wideband satellite receivers must be cross-connected to all four satellite transmit beams. This represents a 6 dB satellite power and bandwidth penalty which more than offsets the advantage of increased antenna gain. In addition, there is a satellite weight penalty due to all the channelization hardware required The satellite power penalty can be reduced if satellite transmitters having a linear DC input to RF output transfer function can be provided. In such cases, the DC power required by an inactive channel is zero and the spacecraft prime power capability doesn't need to be oversized. The power and bandwidth penalty is further reduced as the size of the ground network and the minimum number of satellite channels required increases. Even so, the multibeam FDMA approach does not look attractive.

TABLE 3-4. AVERAGE ANNUAL COST/TERMINAL VS NUMBER BEAMS/ SATELLITE (Ku-BAND 10^2 TERMINALS) (POINT-TO-POINT TV)

SATELLITE BEAMS	LAUNCH VEHICLE	0.20% OUTAGE	0.1% OUTAGE
1	Exp. 2914	85,780	92,165
	Exp. 3914	75,105	81,105
	Shuttle 3914	64,705	70,210
	Exp. A/C	56,450	61,810
	Shuttle A/C	49,480	54,445
	Ded. Shuttle	39,865	44,245
4	Exp. 2914	80,590	85,220
	Exp. 3914	64,400	68,735
	Shuttle 3914	54,590	58,710
	Exp. A/C	42,895	46,440
	Shuttle A/C	36,830	40,230
	Ded. Shuttle	27,650	30,705

2. Satellite Requirements

Satellite requirements for this service, are depicted in Figure 3-4. As shown, the number of required channels varies from 1-to-4-to-40 as the number of terminals in the nationwide network increases from 10-to-100-to-1000 respectively. This is based on an average of 25 terminals per satellite signal in all cases except that involving 10 terminals.

The required satellite power per channel is shown to be quite modest (i.e., less than 4 watts) even though the link carrier-to-noise density (i.e., C/No) requirement is high. Modest channel powers are typical of transmit/receive services since there is a limited number of terminals associated with each satellite signal. As a result, satellite costs can't be widely distributed over the ground complex and channel powers must remain low. It also reflects the relatively low cost of modern Ku-band earth terminals (e.g., $100K), and in this case, the use of a four-beam antenna. The increase in the power per channel, as the number of terminals goes from 10 to 100 occurs because the number of terminals per satellite channel increases from 10 to 25. This increase represents a decrease in the satellite cost per terminal and allows the use of more satellite power. The decrease in the power per channel, as the number of terminals increases from 100 to 1000, results because the per unit ground terminal cost decreases modestly as the size of the "buy" increases, allowing the use of higher performance ground terminals. The increase in the power per channel, when bigger satellites are used, is a result of the corresponding decrease in the cost of providing satellite power.

The percentage of the satellite consumed in handling this service is shown to be quite modest until the number of terminals served reaches 10^3. At this point, 40 satellite TV channels are assumed to be required and the size of the demand has become unrealistic. A 100-terminal network is more representative of a possible requirement. As might be expected, the percentage of the satellite consumed increases as the size of the satellite decreases. A 100-terminal network can easily be served by a Shuttle 3914 or a Shuttle Atlas-Centaur sized payload.

The 3 watt power per channel limit marked on Figure 3-4, defines the maximum allowable power, without coordination, if the satellite-to-satellite separations are 4.5°. Higher power levels are permissible if wider separations are accepted. Conversely, the levels must be lower if the separations are less. This is not a flux density limit. It merely means the two systems have to do frequency planning, employ cross-polarization, tailor their satellite antenna patterns, etc. such as to ensure tolerable levels of system-to-system interference. The basic CCIR requirement applicable to the U.S. (i.e., Region 2) states that coordination is required if the flux densities at the earth's surface exceed:

- -147 dBW/M^2 in any 27 MHz bandwidth and the satellite-to-satellite separations are $\leq 0.44^{\circ}$.
- $-138 + 25 \log \alpha$ dBW/M^2 in any 27 MHz bandwidth where α represents the satellite-to-satellite separation and $0.44^{\circ} < \alpha < 19.1^{\circ}$.
- -106 dBW/M^2 in any 27 MHz bandwidth and the satellite-to-satellite separations are $\geq 19.1^{\circ}$.

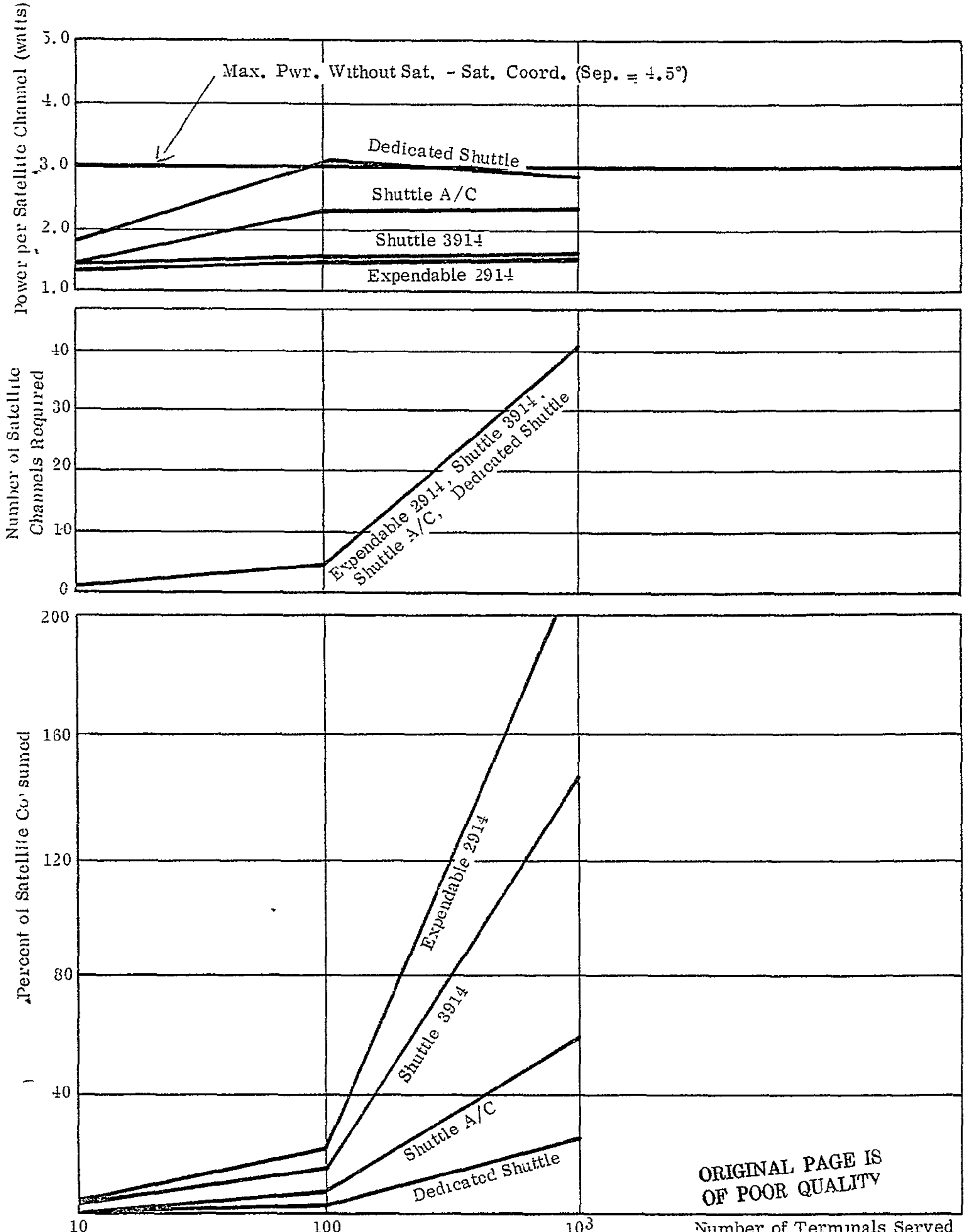

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Figure 3-4. Satellite Power and Capacity Requirements
(4 Beam, Ku-Band Satellite, 0.25% link Outage)
(Point-to-Point TV)

The equation -138 + 25 log α defines the transition curve between the upper and lower flux density founds. Its implications in terms of power per satellite channel are as follows:

$$\text{EIRP (dBW)} + 10 \log_{10} (1/4\pi R^2) - 10 \log_{10} (B/27\times10^6) = -138+25 \log_{10} \gamma$$

where:

- EIRP is the radiated satellite power per channel
- R is the distance from the satellite to the earth and is 3.88507×10^7 meters at a nominal slant range in the U.S. corresponding to a 25° elevation angle.
- B is the band center to band center frequency separation of the satellite channels.

Furthermore:

$$\text{EIRP (dBW)} = P_{sc}+G_s-L_s-M_{BO}$$

where:

- P_{sc} is the output power of the satellite transmitter when operated at saturation.
- G_s is the peak on axis gain of the satellite antenna pointed at the U.S. G_s is about 36 dB for a 4-beam Ku-band satellite. This does not consider any gain enhancement into a particular portion of the country. G_s is about 30 dB for a 1-beam satellite with no gain enhancement for the Southeast.
- L_s is the loss between the satellite transmitter and the antenna feed. It is 1 dB for a Ku-band satellite.
- M_{BO} is the amount of output backoff from satellite transmitter saturation needed to ensure quasilinear operation.

If no backoff is used (i.e., M_{BO}=0) and the band center to band center separation of satellite channels is 27 MHz, the coordination power limits for 1-beam and 4-beam Ku-band satellites are as shown in Figure 3-5. In the case of the "Point-to-Point TV" service, the 4-beam curve shown can be applied directly.

There is one additional Ku-band flux density constraint that should be mentioned It states that another administration (e.g., Canada or Mexico) experiencing flux densities exceeding:

- -105 dBW/M^2 for broadcast reception 99% of the worst month or
- -111 dBW/M^2 for community reception 55% of the worst month can

claim interference. Applying these limits results in allowable flux densities so far above the levels here that they will not be considered further. See Section 4.3.B for a further definition of the broadcast limit.

3. Satellite/Ground Terminal Cost Versus Network Size

Representative average annual costs/per terminal for this service, are shown in Figure 3-6. The figure dramatizes the cost reductions available in going to larger satellites. The modest cost decrease as the number of network terminals increases from 10 to 100 occurs because the number of terminals/per satellite channel increases from 10 to 25. The resulting

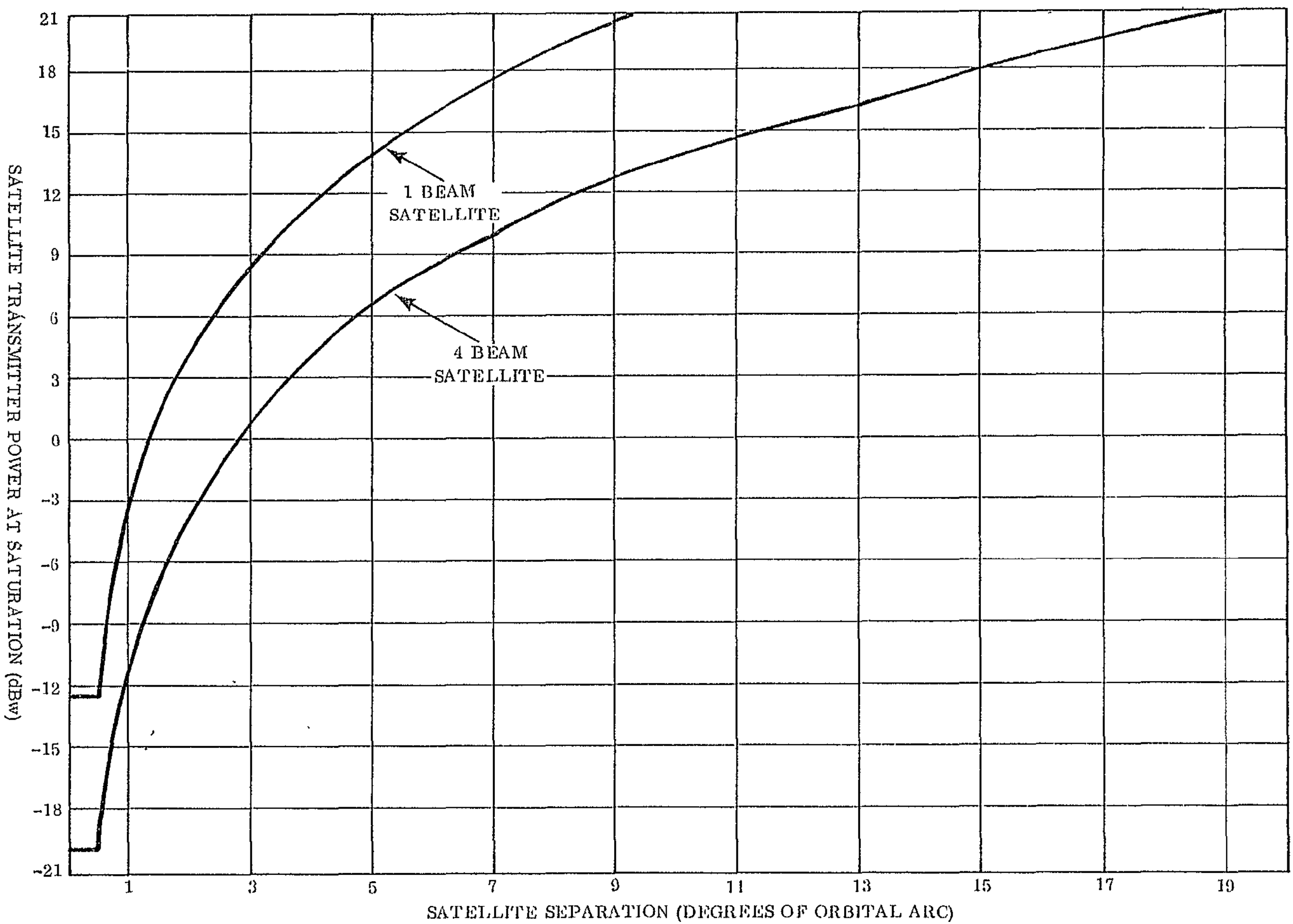

Figure 3-5. Maximum Satellite Power Levels without Coordination (Ku-Band)

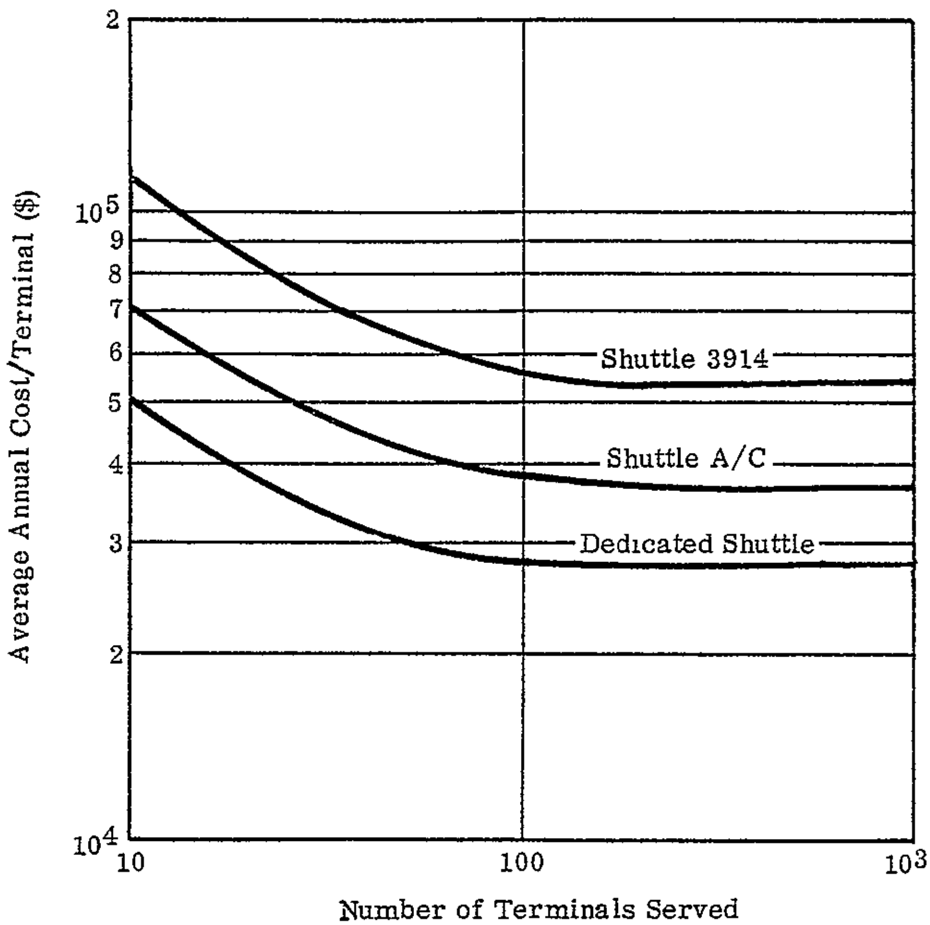

Figure 3-6. Annual Cost vs. Network Size
(4 Beam Ku-band Satellite, 0.20% Outage)
(Point-to-Point TV)

reduction in satellite cost/per terminal produces a lower system cost. As the size of the network increases from 100 to 1000, the only factor causing cost reductions is the increased size of the terminal buy. The cost reductions are almost negligible. This is because: 1) the ground terminal cost reduction was not large (e.g., 25%) and 2) the satellite is the dominating element in system costs (see Section 3.3.A.5).

Cost/per terminal for a network of 100 terminals serviced by a four beam, Shuttle Atlas-Centaur satellite is shown to be about $38K per year. This does not include the cost of the fixed performance equipment (e.g. modems, power supplies, TV cameras and TV monitors). This amounts to $3.17K per month or about $244 per diagnosis. The latter is based on a rural terminal making an average of about three calls per week. It also assumes that the cost of the terminal at the urban medical center is negligible. The latter is a reasonable approximation since terminal costs are substantially less than satellite costs and the urban terminal is shared by 24 rural terminals. The operating scenario associated with this service is described in detail in Section 3.4.D.

4. Ground Terminal Requirements

Curves depicting the trends in ground terminal G/T, EIRP, antenna diameter, receive system temperature, and transmitter power as a function of the number of terminals in the network are presented in Appendix 4. The G/T and EIRP trends track those seen in the satellite power per channel data (See Figure 3-4) except the variation is in the opposite direction (i.e., when satellite power increases the terminal EIRP and G/T requirements decrease). In summary, basic trends are:

- Terminal EIRP and G/T decrease as the size of the satellite increases and the number of terminals in the network varies from 10 to 100.
- Terminal EIRP and G/T experience an almost negligible increase as the size of the network increases from 100 to 1000.

It is not surprising that terminal EIRP and G/T react in the same manner. The system optimization algorithm does a three way tradeoff between terminal EIRP, satellite EIRP and terminal G/T. (See Section 3.4.A.) The earth terminal performance variations are accomplished primarily by varying the size of the antenna. A non-redundant transmitter and receiver is employed and a large antenna (e.g., 10 meters diameter) is involved

For a network of 100 terminals, operating through a four beam Shuttle Atlas-Centaur satellite, the optimum ground terminal parameters are: 1) G/T=37.5 dB/°K, 2) EIRP=75.3 dBw, 3) antenna diameter=9.9 meters, 4) receiver noise termperature=100°K and 5) transmitter power=25 watts. This is a Cassegrain auto tracked antenna, a cooled paramp low noise amplifier, and a TWTA transmitter. Representative deviations, in terminal parameters, that increase system costs by no more than 10% are depicted in Table 3-5. The indicated parameter bounds are observed from the system optimization curves displayed in Appendix 4 As shown, the point of 10% cost increase is reached by varying either the ground terminal EIRP with G/T constant or vice versa. Allowing the terminal

Table 3-5. Bounds on Ground Terminal Parameters
(Ku-Band, 4 Beam Satellite, 0.20% Outage)
10^2 Terminals) (Point-to-Point TV)

Launch Vehicle	Terminal Parameter	Bound Reached By		Bound Reached By	
		G/T Reduction	EIRP Reduction	G/T Increase	EIRP Increase
Shuttle 3914	G/T (dB/°K)	34.5	39 (1)	39 (1)	39 (1)
	EIRP (dBW)	76.3 (2)	74.3	76.3 (2)	88.3
	Antenna Dia. (meters)	8.0	11.0	11.0	11.5
	Receiver Temp. (°K)	200	110	110	130
	Transmitter Power (watts)	50	15	25	280
Shuttle A/C	G/T (dB/°K)	33.5	37.5 (2)	39	37.5 (2)
	EIRP (dBW)	75.3 (2)	73.3	75.3 (2)	82.3
	Antenna Dia. (meters)	7.5	10.5	11.0	10.0
	Receiver Temp (°K)	230	130	110	150
	Transmitter Power (watts)	45	15	20	160
Ded. Shuttle	G/T (dB/°K)	32.5	36.5 (2)	39 (1)	36.5 (2)
	EIRP (dBW)	74.3 (2)	71.3	74.3 (2)	82.3
	Antenna Dia. (meters)	7.5	9.5	11.0	10.0
	Receiver Temp. (°K)	280	130	110	190
	Transmitter Power (watts)	35	10	15	160

NOTES: (1) Corresponds to maximum G/T considered in the study
(2) Corresponds to optimum value.

G/T to decrease appears to be the most attractive option. It gives antenna size reductions in an application where large antennas are inconvenient. When a reduced G/T terminal is operated with a Shuttle Atlas-Centaur satellite, the ground terminal parameters become: 1) G/T = 33 5 dB/°K, 3) EIRP = 75.3 dBw, 3) antenna diameter = 7.5 meters, 4) receive noise temperature =230°K. and 5) transmitter power = 45 watts. This is still a Cassegrain autotracked antenna with a TWTA transmitter. However, the antenna size has been reduced to less than 25 feet and an uncooled paramp or possibly GaAsFet receiver can be employed.

The ground terminal results indicated above are for a terminal located in the Northeastern U.S. and reflect the provision of an extra 7 dB antenna gain into the Southeast by the satellite model. Providing this extra capability causes a reduction in the antenna gain available in the Northeast. The gain available at the edge of the pattern (i.e., 3 dB down point) is 30.5 dB. If no distortion is applied to the eastern beam, the four beam satellite antenna gain in the Northeast can be expected to be about 33 dB. With this gain improvement taken into account, the above terminal parameters become: 1) G/T 31.0 dB/°K, 2) EIRP=72.8 dBw, 3) antenna diameter=6.6 meters, 4) receiver noise temperature=305°K, and 5) transmitter power=30 watts.

Finally, it should be noted that the ratio of uplink to downlink carrier-to-noise (i.e. C/N) ratio for this service is low, about 3.6 (i.e. 5.6 dB) for the four beam Shuttle Atlas-Centaur satellite with 10^2 terminals. The ratios are tabulated on the system optimization curves in Appendix 4. It is shown that the ratio decreases as the satellite size increases. This indicates that the required uplink capability is less as the cost/watt of satellite power becomes less.

5. Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items, are summarized in Table 3-6. Again taking the four beam Shuttle Atlas-Centaur satellite and 10^2 terminals as a representative system, the annual cost per terminal is shown to be $51,620. The total cost per diagnosis, C_D (S), is then determined as follows:

Table 3-6. Breakdown of Total Average Annual Cost/Terminal (Ku-band, 4 beam Satellite, 0.20% Outage, 10^2 Terminals)

(Point-to-Point TV)

Launch Vehicle	Total Annual Cost ($)	Percent of Cost		
		Satellite	Ground Terminal	Fixed
Shuttle 3914	69,380	57	22	21
Shuttle A/C	51,620	44	27	29
Dedicated Shuttle	42,440	36	29	35

$$C_D(S) = \frac{(36,820 \times 1.1 + 14,800)(1 + 1/24)}{3 \times 53} = \$369$$

This cost includes a 10% increase in costs to allow a lower G/T rural terminal. Also included is the rural terminal's fixed equipment cost, (see below), the cost of the urban terminal plus its share of the satellite cost as distributed over 24 rural users, and an average rural terminal call rate of three times per week. These costs are high enough that the service is applicable only to the more serious medical cases. However, they are not completely out of reason.

The fixed items, shown in Table 3-6, include equipment costs of $45,905, based on a buy of 10 items/manufacturer/year, and operator costs for the video cameras. (See Appendix 1 for a detailed breakdown of fixed equipment costs.) Operator costs are based on part time use of a trained hospital or local TV service technician. If the terminal operates 3 times per week, the terminal requires 1.5 hours of operator time/transmission, and the operator is paid $10/hour, and the overhead rate of the hospital or service company providing the operator is 75%, the yearly cost of the operator is $4,095. Fixed equipment tests can be annualized by multiplying capital costs by a factor of 0.233, which provides for capital recovery and maintenance costs (See Section 3.5 for a detailed discussion). When the equipment and operator costs are combined, a yearly cost of $14,800 results.

Table 3-6 shows that costs are evenly distributed among the satellite, ground terminal and fixed items when a Shuttle Atlas-Centaur or larger satellite is used. If any item can be considered dominant, it is the satellite. The indicated distribution of satellite/ground terminal costs is further verified by the sensitivity analysis. Results of this analysis are displayed in Appendix 4. The analysis involved ±10 dB variations of satellite and ground terminal costs with performance held constant. When a four beam Shuttle Atlas-Centaur satellite is paired with 10^3 terminals, a 10 dB reduction of satellite costs produces a 66% decrease in satellite/terminal costs. A corresponding reduction of ground terminal costs produces a 34% decrease.

These results suggest an FDMA satellite, providing higher gain beams, could reduce system costs. For instance, 8 to 16 beams and a corresponding number of channels might be applied in a regional coverage scenario. Bigger satellites, longer satellite lifetimes, shuttle optimized designs, more efficient solar arrays, ion jets, etc., are all possible means of reducing costs further. Further investgation into reasonable picture quality/video camera cost trade-offs could produce cost benefits. A service reconfiguration also has cost reduction potential. For instance, video/audio transmissions, from the urban terminal to the rural terminal might be replaced by audio only transmissions.

B. COMPRESSED BANDWIDTH TV/FACSIMILE

1. Average Annual Cost versus Satellite Channel Bandwidth

Satellite channel bandwidth is varied in the system optimization runs for some services in order to vary the number of user signals/channel. It also changes satellite channel power and cost allocations. Channel bandwidths can be varied from at least 10 MHz to 100 MHz without affecting the satellite transponder block diagram or weight

allocations. It's variation, in this service, permitted an investigation of the impact of eliminating the transponder back-off. As discussed in Section 3.4.D, the back-off varies from 0 dB to 1.6 dB to 5.1 dB as the number of signals/channel increases from 1 to 2 to 3 or more. The corresponding satellite bandwidths are 12 MHz, 24 MHz and 36 MHz. The results of this investigation are summarized in Table 3-7. As shown, there was no benefit from saving the back-off. In fact, the trend is in the other direction; indicating bandwidths even greater than 36 MHz should be considered. Understanding this result requires some insight into the satellite power per channel versus cost per channel curves.

The curves are generated by increasing the number of transmit channels, thereby decreasing the power available per channel and decreasing the portion of spacecraft cost allocated to each channel. This process continues with cost changes being almost directly proportional to power changes (i.e. constant Δ cost/ Δ power) until the weight of each transponder's receiver, frequency converter, channel filter, and transmitter driver begins to approach that of the transmitter. Note that the weight requirements of the prime power source are part of this tradeoff. At this point decreases in the power per channel no longer result in corresponding cost decreases. Rather, the cost trend begins to flatten (i.e. decreased Δ cost/ Δ power) since spacecraft cost allocations per channel are made on a weight basis. A minimum transponder cost, independent of power is reached and spacecraft costs dominate the system optimization. The threshold channel power level, below which below which the cost declines become limited, occurs at about 19 watts. Widening the channel bandwidth and increasing the number of signals/channel causes the system optimization to occur at higher channel powers which represent more cost effective satellite designs.

This service is one where the system optimization should occur at relatively low power densities. The average number of terminals per signal accessing the satellite is only four (See Section 3.4.D) making satellite power expensive. Further, the link carrier-to-noise, C/N, requirement is only about 3 dB (See Section 3.4.D). As a result, increasing the channel bandwidth allows these power densities to be realized in a more cost effective manner. In fact, the savings far outweigh those available from reducing or eliminating the output back-off. In addition, it appears that even wider bandwidths should be employed. Section 3.3.B.3 shows that satellite channel power requirements are less than 5 watts even when a 36 MHz bandwidth is selected.

2. Average Annual Cost Versus Number Beams Per Satellite

This service is a typical example of a situation where four beam FDMA service is not likely to be applicable. It is structured as a teleconferencing service where low duty cycle connections are required across the country. The disadvantages, of trying to provide such demand assigned interconnectivity in a four beam design, were discussed in the description of "Point-to-Point TV" service results. In essence, there are two

Table 3-7. Average Annual Cost vs. Satellite Transponder Bandwidth
(Ku-Band, 0.20% Outage)
(Compressed Bandwidth TV/Facsimile)

Launch Vehicle	Bandwidth	1 Beam		4 Beam	
		10	10^3	10	10^3
Expendable 2914	12 MHz	292,955.	291,125.	383,595.	382,875.
	24 MHz	159,695.	156,685.	196,375.	195,245.
	36 MHz	122,815.	119,976.	137,790.	135,705.
Dedicated Shuttle	12 MHz	92,060.	90,325.	87,840.	86,660.
	24 MHz	55,275.	53,455.	49,245.	48,060.
	36 MHz	47,070.	44,645.	38,610.	37,205.

problems, the extensive cross beam channelization required and the statistical averaging that could occur if all the traffic requirements were lumped into one channel. As a result of the latter, greater total satellite power and bandwidth is required to serve the same number of users with the same probability of blockage. This extra capacity requirement is not addressed in the results presented in Table 3-8. Even so there are few instances where the four beam design produces lower system costs. This is a result of the low satellite power densities associated with this service. In the low power region of the satellite curves, the penalty of having to carry four receivers becomes a burden The smaller the satellite the greater the burden. With all factors considered, one beam configuration has been selected as preferable for the "Compressed Bandwidth TV/Facsimile" service.

3 Satellite Requirements

The low satellite power densities indicated above are verified in Figure 3-7. As shown, two to three watts of channel power is being spread over 36 MHz. The same basic trends in the data, as discussed for the "Point-to-Point TV" service are observed. The only exception is that the power requirements do not increase as the number of terminals increases from 10 to 100 because the average number of terminals/signal accessing the satellite stays constant at four. The overall power level per channel is also very similar to that for the "Point-to-Point TV" service. There are compensating differences in the two services. A lower C/N ratio, due to digital operation and the use of coding, plus a smaller number of terminals/signal accessing the satellite tend to decrease the satellite power required. However, the use of a lower gain (i.e. one beam) satellite antenna and a wider channel bandwidth (i.e. 36 MHz rather than 33 MHz) increases the power needed. Both sets of power requirements are well into the region where the satellite cost trend begins to flatten (See Appendix 2). This indicates channel bandwidths up to 96 MHz or higher need to be considered.

Figure 3-7 shows that the number of satellite channels required increases from 1.3 to 8 to 83.3 as the number of terminals in the network increases from 10 to 100 to 1000. This is a result of placing three signals in each satellite channel and having requirements for 4, 24 and 250 signal accesses. When there are four terminals/access. The figure also shows that satellite capacity requirements are modest until a network size of 10^3 terminals is reached. A reasonable sized network is on the order of 100 terminals. In this case, Shuttle 3914 or Shuttle Atlas-Centaur satellites appear to be attractive choices.

The satellite coordination limits displayed were based on the one beam satellite curve shown in Figure 3-5. However, in this case, the satellite output power backoff and a channel bandwidth wider than 27 MHz must be taken into account. Accordingly,

$$P_{Coord} = P_{Curve} + 5.1 \text{ dB} + 10 \log_{10} (36/27)$$

$$= P_{Curve} + 6.4 \text{ dB}$$

Table 3-8

Table 3-8. Average Annual Cost Per Terminal Vs. Number of Beams Per Satellite
(Ku-Band Satellite, 10^2 Terminals, 36 MHz Bandwidth)
(Compressed Bandwidth TV/Facsimile)

	Launch Vehicle	0.20% Outage	0.1% Outage
1 Beam	Expendable 2914	122,815.	138,170.
	Expendable 3914	105,185.	118,205.
	Shuttle 3914	88,070.	98,805.
	Expendable A/C	75,285.	83,940.
	Shuttle A/C	63,505.	71,010.
	Dedicated Shuttle	47.070.	53,320.
4 Beams	Expendable 2914	137,790	143,975.
	Expendable 3914	110,380.	114,775.
	Shuttle 3914	90,385.	94,780.
	Expendable A/C	67,215	72,065.
	Shuttle A/C	55,890	60,165.
	Dedicated Shuttle	38,610	42,405.

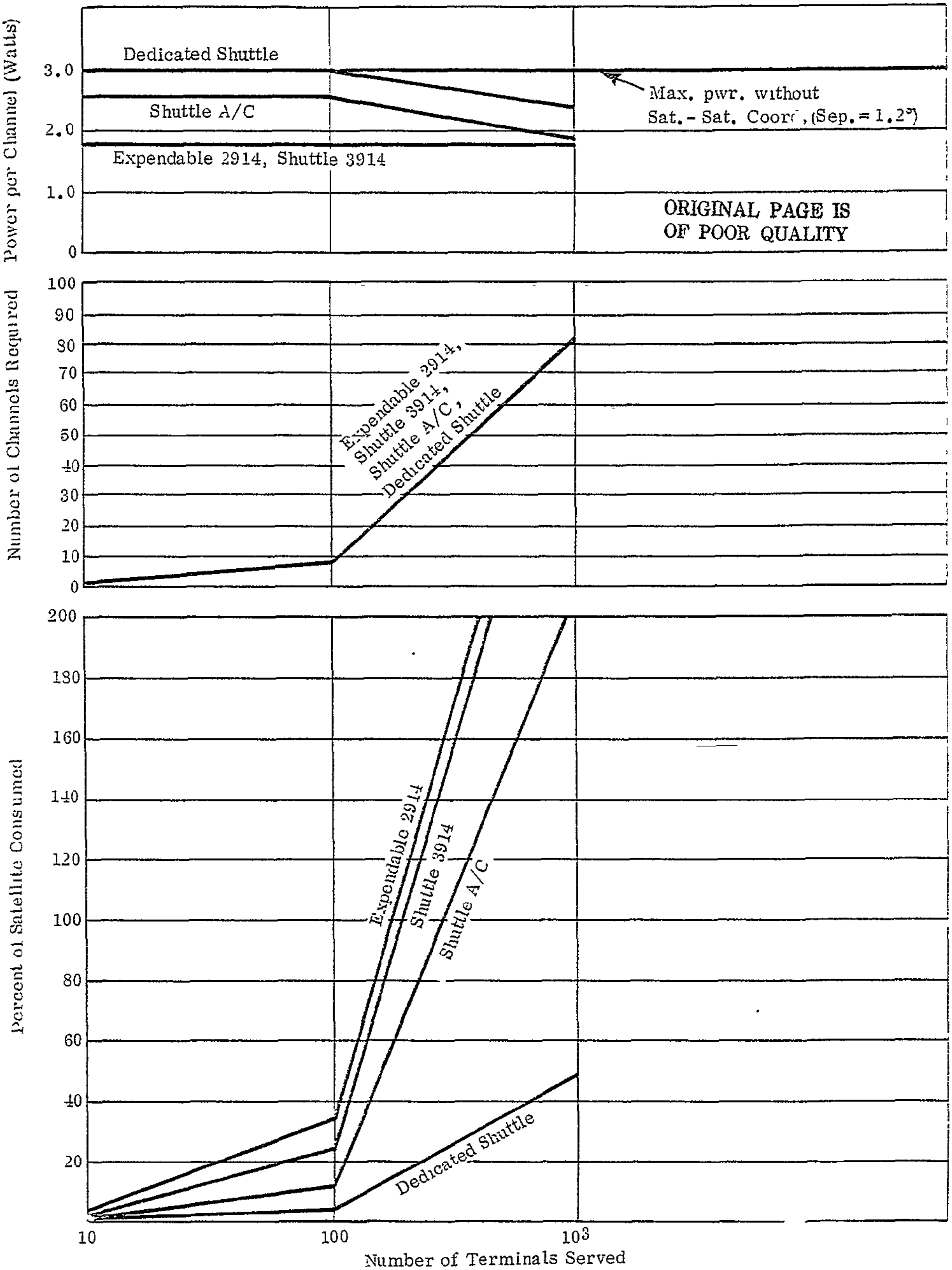

Figure 3-7. Satellite Power and Capacity Requirements (Ku-Band, 1 Beam, 0.20% Link Outage, 36MHz) (Compressed Bandwidth TV/Facsimile)

4. Satellite and Ground Terminal Cost Versus Network Size

Average annual cost per user terminal for the satellite and ground complex is depicted in Figure 3-8. The cost decrease, observed for the "Point-to-Point TV" service as the number of terminals increases from 10 to 100, is not present because the number of terminals per satellite access is constant. The same negligible decrease in cost due to an increase in the size of the buy, as the number of network terminals increases from 10^2 to 10^3, is observed. The cost per terminal for a network of 100 served by a one beam Shuttle Atlas-Centaur satellite is shown to be about $63K per year. This is exclusive of the cost of fixed performance equipment. It amounts to about $220 per terminal per call or a total of $440 per call since a full duplex capability is provided. The cost per terminal per call is seen to be about the same as for the "Point-to-Point TV" service. This is somewhat surprising in view of the lower link C/N. However, in this case the average call duration is 1.5 hours rather than 0.5 hours. The cost per call is based on each terminal handling an average of 5.5 calls per week (See Section 3.4.D).

5. Ground Terminal Requirements

Curves depicting the trends in ground terminal G/T, EIRP, antenna diameter, receive system temperature, and transmitter power as a function of the number of terminals in the network are presented in Appendix 4. The G/T variations are in the opposite direction to those observed in the satellite power/channel curves (See Figure 3-7). However, the terminal EIRP is constant regardless of the number of terminals in the network. This is not surprising since the G/T and satellite power per channel variations are modest (i.e. 1 dB to 1.5 dB). The G/T variations are all increases accomplished by employing a larger diameter antenna. A larger antenna makes a modest reduction of transmitter power possible.

For a network of 100 terminals served by a one beam Shuttle Atlas-Centaur satellite, the optimum terminal parameters are: (1) G/T = 37.5 dB/^{o}K, (2) EIRP = 73.3 dBW, (3) antenna diameter = 9.9 meters, (4) receiver noise temperature = 100^{o}K and (5) transmitter power = 15 watts. These are equivalent to a Cassegrain autotracked antenna, a cooled paramp low noise amplifier, and a TWTA transmitter and are very similar to the terminal for the "Point-to-Point TV" service. Thus, the lower link C/N_o requirement results in a lower satellite EIRP/link. The satellite power per channel is almost the same. However, the antenna gain is lower and the channel power is split between three signals.

Variations in the terminal parameters that increase system costs by no more than 10% are depicted in Table 3-9. The parameters are read from the system optimization curves in Appendix 4. The most effective way, for relieving the problems of a 10 meter antenna and a cryogenically cooled receiver, involves reducing the G/T by about 3.5 dB. For a network of 100 terminals operating with a Shuttle Atlas-Centaur satellite, the terminal parameters become: (1) G/T = 34.0 dB/^{o}K, (2) EIRP = 73.3 dBW, (3) antenna diameter =

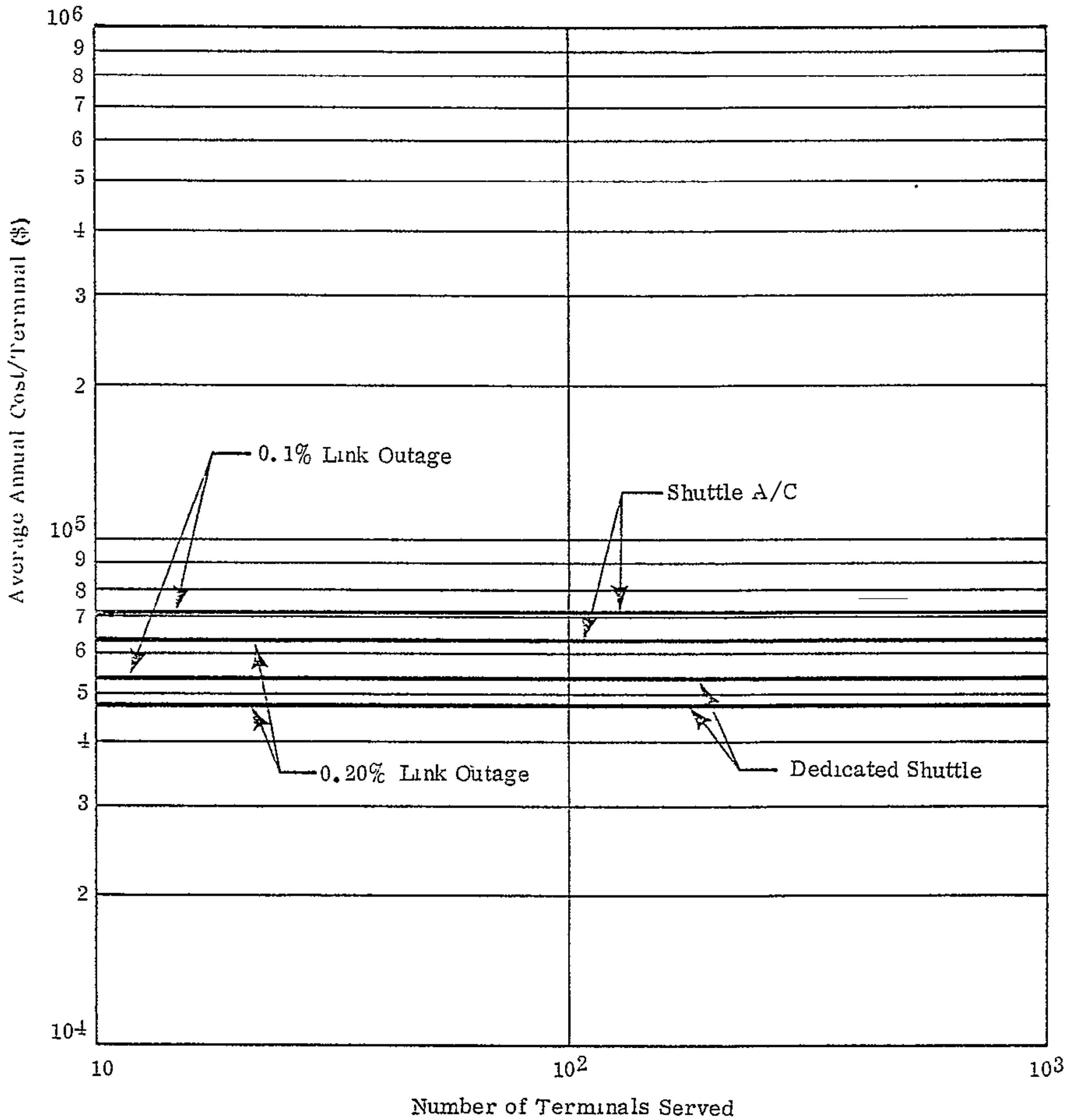

Figure 3-8 Annual Cost vs. Network Size (1 Beam Ku-Band satellite, 36 MHz Bandwidth) (Compressed Bandwidth TV/Facsimile)

Table 3-9. Bounds on Ground Terminal Parameters (Ku-Band, 1 Beam Satellite, 0.20% Outage, 10^2 Terminals, 36 MHz Bandwidth (Compressed Bandwidth/TV Facsimile)

Launch Vehicle	Terminal Parameter	Bound Reached By G/T Reduction	Bound Reached By EIRP Reduction	Bound Reached By G/T Increase	Bound Reached By EIRP Increase
Shuttle A/C	G/T (dB/°K)	34.0	37.5 (1)	39.0 (2)	37.5 (1)
	EIRP (dBw)	73.3 (1)	68.3	73.3 (1)	88.3
	Antenna Dia. (meters)	8.0	10.0	11.0	10.5
	Receiver Temp. (°K)	230	110	110	12.5
	Transmitter Power (watts)	25.0	5.0	12.6	445
Dedicated Shuttle	G/T (dB/°K)	33.5	37.0 (1)	39.0 (2)	37.0 (1)
	EIRP (dBw)	72.3 (1)	68.3	72.3 (1)	90.3
	Antenna Dia. (meters)	7.5	10.0	11.0	10.0
	Receiver Temp. (°K)	230	30	110	150.
	Transmitter Power (watts)	20.0	5.0	10.0	795

(1) Corresponds to Optimum Value
(2) Corresponds to Maximum G/T considered in the study

8 meters, (4) receiver noise temperature = 230°K, and (5) transmitter power = 25 watts. The antenna size has been reduced to a little over 25 feet and an uncooled paramp or possibly GaAsFet receiver can be employed.

As in the case for the four beam satellite antenna, some further improvement can be realized if the 7 dB advantage to the Southeast is eliminated. However, the satellite antenna gain in the Northeast increases by only 1 dB instead of 2.5 dB because the Southeast advantage trades off against the gain in all areas of the country rather than that in the Northeast alone. As a result, eliminating extra gain into the Southeast has a negligible impact on one beam satellites.

The uplink-to-downlink C/N ratios for this service are displayed on the system optimization curves in Appendix 4. A value of 12 (i.e. 10.8 dB) is shown for the one beam Shuttle Atlas-Centaur satellite serving 10^2 terminals. This is considerably higher than the corresponding ratio determined for the "Point-to-Point TV" service. It again points to the higher cost of satellite EIRP.

6. Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items, are summarized in Table 3-10. The costs shown, when a Shuttle Atlas-Centaur satellite is selected, are $141,175 annually per terminal and $495 per call per terminal. The fixed items include the fixed equipment costs, the price of a truck and trailer, and the salary of an operating crew of two individuals. The fixed equipment capital cost is $79,270 based on a buy of 10 items per manufacturer per year. (See Appendix 1 for a detailed breakdown of fixed equipment costs.) This converts to an $18,470 annual cost when the 0.233 annualizing factor is applied. The capital cost of the truck and trailer is estimated at $20,000. A 10% rate of return and five-year lifetime results in an annualizing factor of 0.2638. Combining this with a 7% allowance for yearly operation and maintenance, the annual cost for the vehicle becomes $6,675. The operating crew is composed of one engineer earning $18,000 per year and one technician earning $12,000 per year. A 75% overhead rate is assumed for the organization providing the service. This results in a yearly cost for operators of $52,500. The total yearly cost for fixed items is then $77,645.

The major cost items for this service are clearly the satellite and the operators. Further, the operator and vehicle cost given are conservative in view of the fact that the terminal antenna diameter is about 8 meters. The breakdown of costs between the satellite and earth terminal is further verified by the sensitivity analysis. Results of this analysis are displayed in Appendix 4. When a one-beam Shuttle 3914 satellite serves 10 terminals, a 10dB reduction of satellite costs results in a 77% decrease in overall costs. A corresponding reduction of ground terminal costs results in a 20% decrease.

One potential means of making this a more cost-effective service involves applying high burst rate (i.e., wide bandwidth) TDMA multibeam satellite technology.

Table 3-10

Table 3-10. Breakdown of Total Average Annual Cost/Terminal
(Ku-Band System, 1 Beam Satellite, 10^2 Terminals, 36 MHz Bandwidth)
(Compressed Bandwidth/TV Facsimile)

Launch Vehicle	Total Average Annual Cost ($)	Cost per Terminal per Call (1)	Percent of Cost		
			Satellite	Ground Terminal	Fixed
Shuttle A/C	141,175.	495	34.	11.	55.
Dedicated Shuttle	124,745.	435	26.	12.	62.

(1) $\text{Cost/Terminal/Call} = \dfrac{\text{Total Cost/Terminal/Year}}{\text{286 Calls/Year}}$

As previously discussed, an FDMA multibeam approach is not likely to be attractive due to the satellite weight penalty for extensive channelization. The TDMA modem costs will substantially increase the fixed equipment costs but will significantly reduce satellite costs. Further, reducing the satellite output power backoff and employing higher gain satellite antennas will result in lower performance ground terminals. Ground antenna sizes of less than 4.5 meters are necessary in order to make the existing assumptions on the vehicle and operating crew valid.

Additional improvements can come from the use of wider satellite channel bandwidths, bigger satellites, longer life/higher reliability satellites, shuttle optimized designs, more efficient solar arrays, ion jets, etc. A further substantial improvement results if conferences are structured to average no more than one hour in duration rather than 1 1/2 hours. The alternative of providing this as a combined TV/facsimile/wideband data service with terminals sold to individual organizations should also be considered. This will result in higher satellite/terminal and fixed equipment charges but will substantially reduce the operator charges. The possibility of using even lower data rate (e.g., 1.5 Mbps) compressed bandwidth TV should be evaluated to see if adequate quality is available.

C. VOICE/FACSIMILE (FDMA)

1. Average Annual Cost Versus Satellite Channel Bandwidth

Satellite channel bandwidth variations were examined in the "Voice/Facsimile" service. In view of the results in the "Compressed Bandwidth TV/Facsimile" service and the narrow bandwidth of this service, no attempt was made to eliminate the satellite backoff. The lower bound of the search was extended no further than 2 MHz. The results are displayed in Table 3-11. Once again, increasing the bandwidth is shown to result in lower costs. However, the rate of cost decrease does seem to level off at a bandwidth of about 15 MHz. This can be expected since this service will optimize at a higher satellite power density than the "Compressed Bandwidth TV/Facsimile" service. A relatively large average number of terminals are associated with each satellite access (i.e., 17). Consequently, satellite power is comparatively inexpensive. Further, the link C/N requirement is about 11 dB since a digital capability incorporating no error correction coding/decoding is assumed. The bandwidth selected for all further tradeoffs was 15 MHz.

2. Average Annual Cost vs Number of Beams per Satellite

As in the TV/facsimile service, a four-beam FDMA satellite cannot be used advantageously. Low duty cycle demand assignment connections are required all across the country. However, the excess satellite capacity needed to ensure the required probability of blockage may not be great. For instance, at a network size of 10^4 terminals, 588 satellite signal accesses must be available in a one-beam satellite

Table 3-11. Average Annual Cost Per Terminal Vs. Satellite Transponder Bandwidth (Ku-band Satellite, 0.20% Link Outage) (Voice/Facsimile)

Launch Vehicle	BW (MHz)	1 Beam		4 Beams	
		10^2 Term.	10^4 Term.	10^2 Term.	10^4 Term.
Shuttle 3914	1.96	10,925.	8,810.	9,015.	7,320.
	7.84	8,840.	6,625.	6,325.	4,555.
	15.68	8,670.	6,430.	5,950.	4,125.
	31.36	8,665.	6,400.	5,925.	4,040.
Shuttle A/C	1.96	9,025.	7,050.	6,885.	5,285.
	7.84	7,730.	5,680.	5,335.	3,720.
	15.68	7,600.	5,545.	5,170.	3,505.
	31.36	7,570.	5,510.	5,150.	3,455.

design. This results in an average of 36.75 accesses required on each of the cross connects of a four-beam design. The access blocks are large enough that considerable statistical averaging is available. Costs for the two satellite design approaches are compared in Table 3-12 without considering the excess channelization requirements of the four-beam case. When the latter are taken into account, it is expected that the two approaches will be approximately equal in cost. Consequently, in the interest of design simplicity, a one-beam approach is adopted for further evaluation of this service.

3. Satellite Requirements

The high satellite power densities indicated above are verified in Figure 3-9. As shown, 20 to 90 watts of channel power is being spread over 15 MHz of bandwidth. The basic trend of the power per channel curves is downward as the number of terminals increases. This is because per unit terminal costs decrease as the size of the ground terminal buy increases. However, occasional reversals of the basic trend are observed. These are a result of modest changes in the slope (i.e., Δcost/Δperformance) of the ground terminal data curves as the size of the buy increases. The exact balance point between the satellite and the ground terminal is a function of the composite performance required of the two and the slope of the two cost-performance curves. A "flatter" G/T curve causes a slightly higher G/T and vice versa. Such reversals in the basic trend are made possible by the "mildness" of that trend.

Figure 3-9 shows that the number of required satellite channels increases from 0.05 to 0.52 to 5.25 to 52.5 as the number of terminals in the network increases from 10^2 to 10^3 to 10^4 to 10^5. This is a consequence of placing 112 signals in each satellite channel and employing a constant factor of 17 terminals/signal accessing the satellite (see Section 3.4.D for an operating scenario). The figure also shows that the satellite capacity requirements are reasonable until a network of 10^5 terminals is reached. The more likely network size is in the range of 10^3 to 10^4 terminals. A Shuttle Atlas-Centaur satellite appears an excellent choice for serving such a network. It is interesting to note that at a network size of 10^4 terminals, the capacity requirements for a Shuttle 3914 satellite are greater than those for an Expendable 2914 satellite. This is because of the unusually high power/channel required on a Shuttle 3914 satellite at this point.

The satellite coordination limits displayed are based on the one-beam satellite curve shown in Figure 3-5. In this case, the satellite output power backoff and a channel bandwidth of less than 27 MHz must be taken into account. A channel center-to-channel center spacing of 18 MHz is reasonable for this service, accordingly:

$$\begin{aligned} P_{Coord} &= P_{Curve} + 5.1 \text{ dB} + 10 \log_{10}(18/27) \\ &= P_{Curve} + 3.3 \text{ dB} \end{aligned}$$

Table 3-12. Average Annual Cost Per Terminal Vs. Number of Beams Per Satellite, (Ku-Band Satellite, 0.20% Link Outage, 15.68 MHz Bandwidth) (Voice/Facsimile)

Launch Vehicle	1 Beam		4 Beams	
	10^2	10^4	10^2	10^4
Exp. 2914	9,895.	7,345.	6,810.	4,895.
Exp. 3914	9,265.	6,960.	6,305.	4,420.
Shuttle 3914	8,670.	6,430.	5,950.	4,125.
Exp. A/C	8,080.	5,960.	5,440.	3,715.
Shuttle A/C	7,600.	5,545.	5,170.	3,505.
Ded. Shuttle	6,830.	4,925.	4,650.	3,110.

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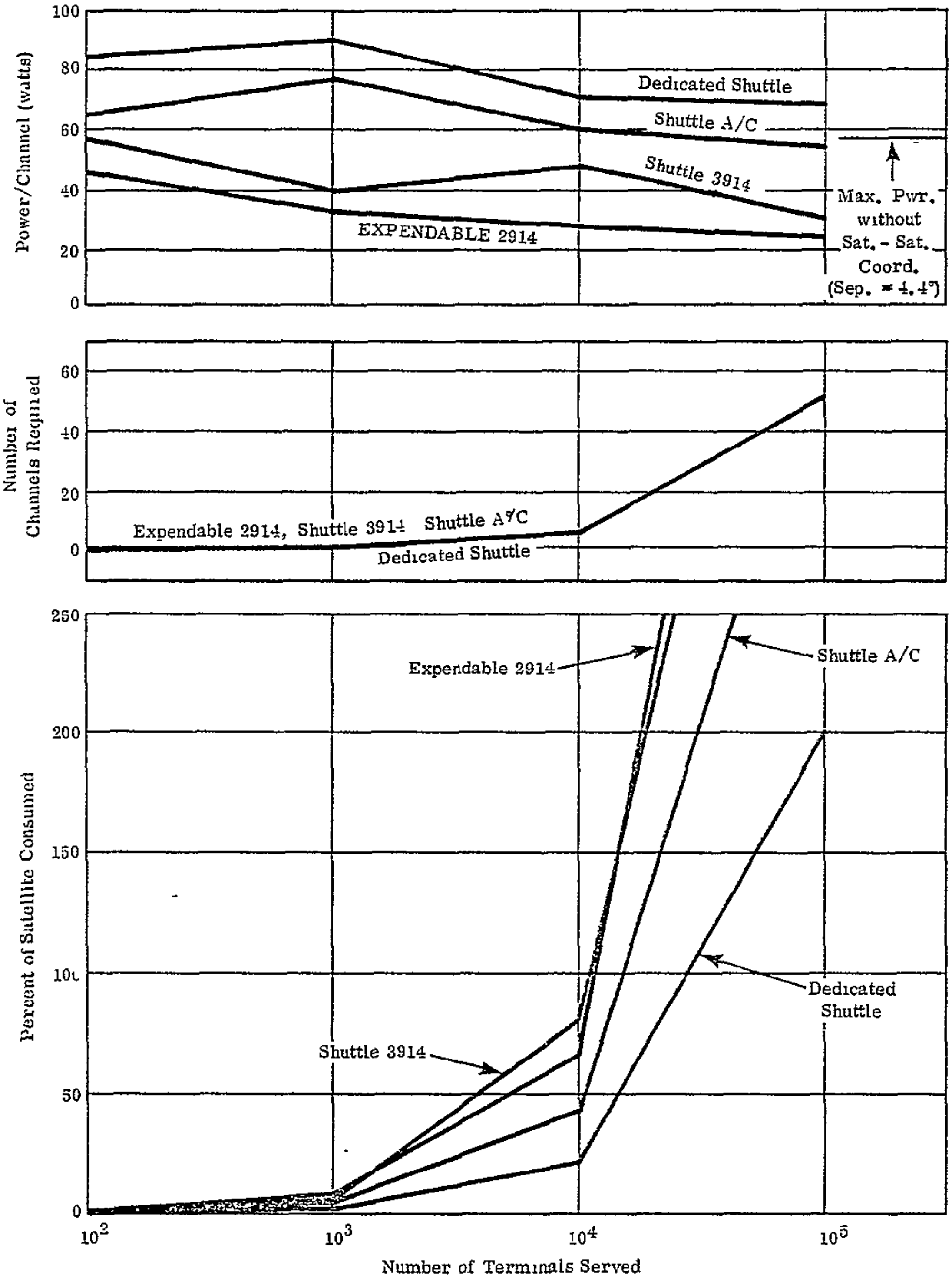

Figure 3-9. Satellite Power and Capacity Requirements
(Ku-Band, 1 Beam, 0.20% Link Outage, 15.68 MHz)
(Voice/Facsimile)

4. Satellite and Ground Terminal Cost versus Network Size

Average annual cost per user terminal excluding fixed equipment is depicted in Figure 3-10. A steady downward trend in the cost is observed as the size of the network and the ground terminal buy increases. This is exactly as expected. The average annual cost per terminal for a Shuttle Atlas-Centaur satellite serving a network of 10^4 terminals is about \$5.5K. This amounts to about \$54 per terminal per call or about \$108 total cost per call since a full duplex capability is provided. The cost per call is based on each terminal handling an average of two calls per week. Each call averages one hour in duration (see Section 3.4.D). The modest costs are as expected based on the relatively low link performance requirements and an average call duration of only one hour.

5. Ground Terminal Requirements

Curves depicting the trends in ground terminal G/T, EIRP, antenna diameter, receive system temperature, and transmitter power as a function of the number of terminals in the network are presented in Appendix 4. The G/T variations are in the opposite direction to those observed in the satellite power per channel curves (see Figure 3-9). So are the terminal EIRP variations when the Shuttle Atlas-Centaur satellite is the choice. However, when the Shuttle 3914 satellite is chosen, the terminal EIRP variations follow those of the satellite power per channel curves. In the first case, all aspects of ground terminal performance trades off with satellite performance. In the second, only the ground terminal G/T does. The latter is believed to be a consequence of the higher cost/watt of satellite power when the Shuttle 3914 satellite is used. When the Shuttle Atlas-Centaur satellite is used, the terminal performance variations are accomplished by changing transmitters and receivers while the antenna diameter remains constant. The constant antenna diameter is about 4.5 meters, which is just below a break point in the Ku-Band antenna performance and cost curves. (See Section 3.6). When the Shuttle 3914 satellite is used, the terminal G/T variations are accomplished primarily by changing antennas. The antenna size varies between about 4.5 meters and 6 meters. In other words, it moves in large increments across the break point in the Ku-Band antenna performance/cost curves. This results in large swings in the terminal transmitter requirements (i.e., 2 watts to 8 watts) since the EIRP variations are in the opposite direction from the G/T and antenna variations.

When a one-beam Shuttle Atlas-Centaur satellite serves 10^4 terminals, the optimum terminal parameters are: (1) G/T = 28 dB/°K, (2) EIRP = 61.3 dBW, (3) antenna diameter = 4.4 meters, (4) receiver noise temperature = 260°K and (5) transmitter power = 5 watts. This is a Cassegrain antenna with a manual steering capability, an uncooled parametric amplifier, or possibly GaAsFet receiver, and a GaAsFet solid-state transmitter. It is a terminal of modest requirements such as might be expected for this service.

Deviations in the terminal parameters that increase system costs by no more than 10% are depicted in Table 3-13. The bounding parameters are read from the

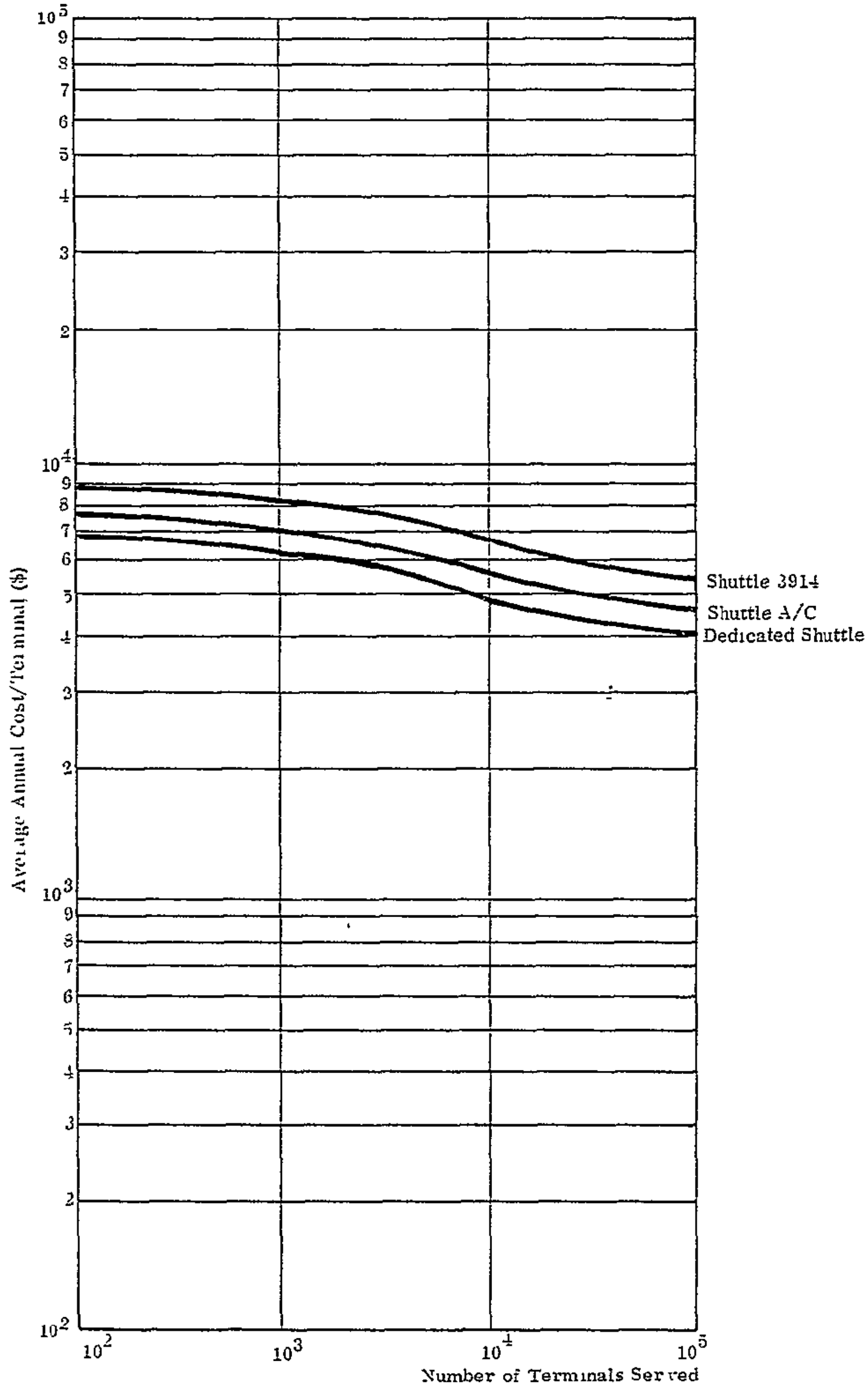

Figure 3-10. Average Annual Cost/Terminal vs. Network Size (Ku-Band, 1 Beam Satellite, 15.68 MHz, 0.20% Link Outage) (Voice/Facsimile)

Table 3-13

Table 3-13. Bound on Ground Terminal Parameters
(Ku-Band, 1 Beam Sat., 0.20% Outage, 15.68 MHz Bandwidth)
(Voice/Facsimile)

	Termianl Parameter	Bound Reached by		Bound Reached by	
		G/T Reduction	EIRP Reduction	G/T Increase	EIRP Increase
Shuttle 3914 (2)	G/T (dB/°K)	25.5	28.0 (1)	31.0	28.0 (1)
	EIRP (dBW)	63.3 (1)	55.3	63.3 (1)	68.3
	Antenna Dia. (Meters)	4.0	4.5	6.5	4.5
	Receiver Temp. (°K)	450	265	305	265
	Transmitter Power (Watts)	10.	1.5	3.5	25
Shuttle A/C (3)	G/T (dB/°K)	25.5	28.0 (1)	31.0	28.0 (1)
	EIRP (dBW)	61.3 (1)	55.3	61.3 (1)	67.3
	Antenna Dia. (Meters)	4.0	4.5	6.0	4.5
	Receiver Temp. (°K)	450	265	265	265
	Transmitter Power (Watts)	6.0	1.5	2.5	20

Notes: (1) Corresponds to optimum point.
(2) 10^2 Terminals in the network.
(3) 10^4 Terminals in the network.

system optimization curves depicted in Appendix 4. The most effective way for relieving the terminal subsystem requirements is to reduce the G/T by 2.5 dB. When a one-beam Shuttle Atlas-Centaur satellite serves 10^4 terminals, the terminal parameters become: (1) G/T = 25.5 dB/°K, (2) EIRP = 61.3 dBW, (3) antenna diameter = 4 meters, (4) receiver noise temperature = 450°K, and (5) transmitter power = 6 watts. This is a 13-foot antenna with a GaAsFet low noise receiver and a GaAsFet solid-state transmitter. No significant improvement in these requirements results from eliminating the 7 dB of satellite antenna gain advantage provided to the Southeast.

The uplink-to-downlink C/N ratios for this service are displayed on the system optimization curves in Appendix 4. A value of about 10 applies when a one-beam Shuttle Atlas-Centaur satellite serves a network of 10^4 terminals. This is less than the corresponding ratio indicated for the "Compressed Bandwidth TV/Facsimile" service (i.e., 12), but not as little as might be expected based on the difference in the number of terminals per satellite access (i.e., 17 as compared to 4). The difference makes satellite power less expensive but this is offset by more inexpensive ground transmitters due to a large ground network and terminal buy (i.e., 10^4 terminal network as compared to a 10^2 terminal network).

6. Total System Cost Breakdown

Total system annual costs per terminal, including the fixed performance items, are summarized in Table 3-14. The costs for a Shuttle Atlas-Centaur satellite are $9,475 per terminal and $90 per call per terminal. The fixed items included in the cost tables are for fixed equipment. No special operators are required. The fixed equipment capital cost is $17,080 based on a buy of 10^3 items per manufacturer per year (see Appendix 1 for a breakdown of the fixed equipment cost). This converts to a S3,980 annual cost when the 0.233 annualizing factor is applied.

The major cost items for the service are clearly the ground terminals and the fixed equipment. The breakdown of the costs between the satellite and earth terminals is further verified by the sensitivity analysis. Results of this analysis are given in Appendix 4. When a one-beam Shuttle 3914 satellite serves 10^2 terminals, a 10 dB reduction of ground terminal costs results in a 78% decrease in satellite/ground terminal costs. A similar reduction of satellite costs produces a 40% decrease in satellite/ground terminal cost.

Although the above costs appear reasonable, further cost reductions are possible. The use of error correction coding/decoding equipment can substantially reduce link performance requirements. A lower operating frequency such as C-Band or S-Band can substantially reduce ground terminal and system costs. A more detailed tradeoff of facsimile and audio equipment cost and performance also might produce modest cost reductions.

Table 3-14. Breakdown of Total Average Annual Cost Terminal (Ku-band, 1 Beam Satellite 0.20% Link Outage, 15.68 MHz Bandwidth)
(Ku-Banc (Audio Fax Teleconferencing Voice/Facsimile)

(Voice/Facsimile)

Launch Vehicle	Total Average Annual Cost ($)	Cost Per Terminal Per Call($)(1)	Percent of Cost In:		
			Satellite	Ground Terminal	Fixed
Shuttle 3914 (2)	16,870	165	14	37	49
Shuttle A/C (3)	9,475	90	18	40	42

Notes: (1) $\text{Cost/Terminal/Call} = \dfrac{\text{Total Cost/Terminal/Year}}{\text{104 Call/Year}}$

(2) 10^2 Terminals in the network.

(3) 10^4 Terminals in the network.

Finally, if network sizes beyond 10^4 terminals can be promoted, stamped antenna technology and LSI circuit designs for the fixed equipment become practical.

D. MULTICHANNEL VOICE/ DATA

1. Average Annual Cost versus Satellite Channel Bandwidth

An optimum satellite channel bandwidth search, similar to that conducted for the Voice/ Facsimile service, was conducted for this service. However, the bandwidth requirements per signal were wide enough that eliminating the satellite output backoff could be considered. The results are given in Table 3-15. In the case of the 1.7 MHz bandwidth, no output backoff is required. At 3.4 MHz, the backoff is 1.6 dB. For the other two bandwidths, the backoff is 5.1 dB. Obviously, the cost savings available from widening the bandwidth overpowers those produced by eliminating the backoff. Further, it again appears that much wider channel bandwidths (e.g., 95.2 MHz) can produce significant cost savings and should be considered. In view of previous results, this is not surprising. In fact, the need for wide channel bandwidths is stronger here than for any of the previous services. Digital signals and error correcting coding/ decoding are employed producing a link C/ N of only about 3 dB. Further, satellite power is expensive since only one terminal is associated with each signal accessing the satellite. The impact of these two factors is a very low satellite power density requirement. As a result, very wide channel bandwidths are needed to produce power requirements in the cost-effective region of the satellite performance/ cost curves (i.e., > 10 watts). The bandwidth selected for all further tradeoffs is 27.2 MHz.

2. Average Annual Cost Versus Number of Beams Per Satellite

This is a service where a four-beam FDMA satellite might be used to advantage. A fixed trunking capability and a large number of satellite accesses are required. If the fixed trunking requirements are known in advance, the beam-to-beam crossconnecting channelization can be efficiently planned. Further, if the number of satellite accesses is large, a big satellite and wideband cross connecting channels can be justified. A big satellite suffers less impact from the multiple receivers needed in a multibeam FDMA satellite. Wideband channels produce a more efficient satellite design as indicated above. Average annual costs for the one-beam and four-beam approaches are compared in Table 3-16. The cost differences are not large. The four-beam approach enjoys an advantage when Atlas-Centaur sized satellites or larger are are used. Based on the implementation of a reasonably large network, the four-beam FDMA approach has been tentatively chosen for further consideration. A one-beam system may be equally applicable.

Table 3-15. Average Annual Cost/Terminal Vs Satellite Transponder Bandwidth (Ku-Band, 0.20% Link Outage) (Multichannel Voice/Data)

Launch Vehicle	BW MHz	2 Beams		4 Beams	
		10 Term.	10^3 Term.	10 Term.	10^3 Term.
Shuttle 3914	1.7	744,390.	742,645.	975,175.	973,865.
	3.4	380,800.	378,710.	490,940.	489,560.
	13.6	116,975.	113,755.	130,420.	128,455.
	27.2	72,120.	68,895.	71,980.	69,725.
Dedicated Shuttle	1.7	321,220.	319,140.	326,785.	325,355.
	3.4	169,385.	167,440.	168,385.	166,590.
	13.6	59,400.	56,905.	52,510.	50,505
	27.2	40,385.	37,845.	32,865.	30,835.

Table 3-16. Average Annual Cost/Terminal Vs Number of Beams Beams/Satellite (Ku-Band, 10^2 Term., 27.2 MHz) (Multichannel Voice/Data)

	Launch Vehicle	Link Outage 0.20%	0.1%
1 Beam	Exp. 2914	98,125.	106,325.
	Exp. 3914	85,130.	92,535.
	Shuttle 3914	72,120.	79,050.
	Exp. A/C	62,080.	68,145.
	Shuttle A/C	52,885.	58,930.
	Ded. Shuttle	40,385.	45,580.
4 Beams	Exp. 2914	107,880.	113,185.
	Exp. 3914	86,980.	91,120.
	Shuttle 3914	71,980.	76,120.
	Exp. A/C	55,030.	58,945.
	Shuttle A/C	46,125.	49,880.
	Ded. Shuttle	32,865.	36,130.

3.0 Satellite Requirements

The low satellite power densities indicated above are verified in Figure 3-11. As shown, about 1 to 2 watts of satellite power is spread over 27 MHz. The basic trend of the power per channel curves is flat as the number of terminals increases. This is because only the size of the terminal buy varies as the network size increases from 100 to 1000. This factor does produce a modest decrease in the satellite power/ channel requirements when Shuttle Atlas Centaur and Dedicated Shuttle satellites are used. Notice that the "flatness" of the trend is also due to the low powers chosen which are on the flat portion of the satellite cost/performance curves where little benefit is realized from reducing channel power. The figure also shows the number of satellite channels required increases from 0.6 to 6.3 to 62.5 as the number of terminals increases from 10 to 100 to 1000. Sixteen signals access each satellite channel and there is one terminal per signal accessing the satellite (see Section 3.4.D for an operating scenario). The figure also shows that the satellite capacity requirements are modest until a network size of 10^3 terminals is reached. Such a network size might be attainable in the period prior to 1985. As a result, a Dedicated Shuttle sized satellite may be required.

The satellite coordination limits depicted are based on the four-beam satellite curve shown in Figure 3-5. However, in this case, a satellite output power backoff must be considered. Since the channel bandwidth is the same as that applicable in the coordination limit regulation, no bandwidth adjustments need to be made. Accordingly:

$$P_{Coord} = P_{Curve} + 5.1 dB$$

4.0 Satellite and Ground Terminal Cost Vs Network Size

Average annual cost per user terminal for the satellite and ground terminal, excluding fixed equipment, is depicted in Figure 3-12. The almost inobservable downtrend as the size of the network increases from 10^2 to 10^3 is due to the increase in the size of the terminal buy. Other than that, the relationship between the satellite and ground terminal remain the same and costs are constant. The average annual cost per terminal for a Dedicated Shuttle satellite serving a network of 10^2 terminals is about \$33,800. This amounts to about \$2,730 per terminal per month or about \$5,460 total cost per month for a full duplex capability. These costs appear high, but a continuous high data rate capability is being provided. Notice that the total cost per duplex voice channel is only \$455 per month. If this channel handles an average of three calls per day, the cost/ call is only about \$5.

5.0 Ground Terminal Requirements

Curves depicting the trends in ground terminal G/ T, EIRP, antenna diameter, receive system temperature, and transmitter power as a function of the number of terminals in the network are presented in Appendix 4. No terminal G/ T or EIRP variations are observed if the Shuttle 3914 satellite is the choice. This is in complete

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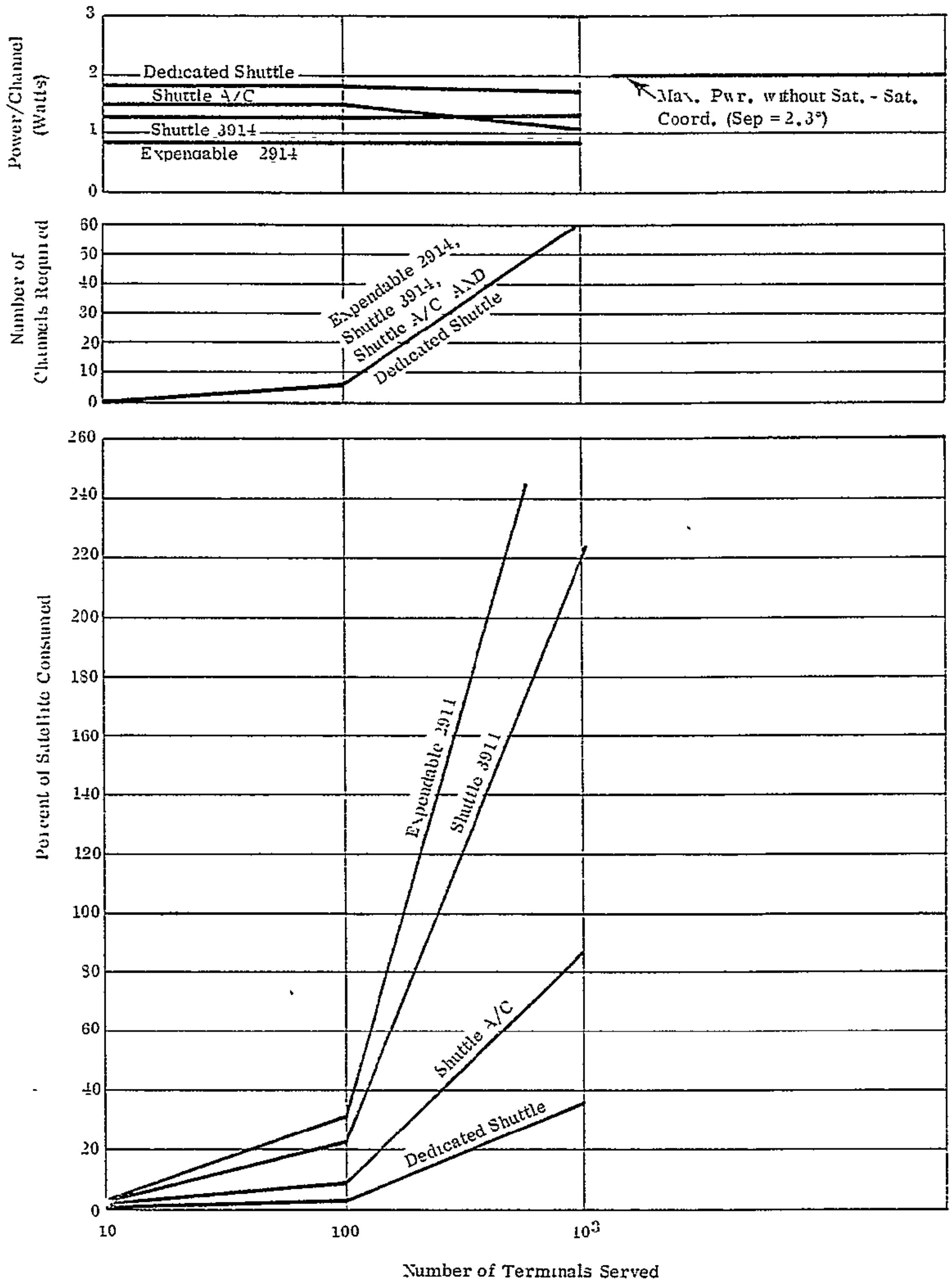

Figure 3-11. Satellite Power and Capacity Requirements (Ku-Band, 4 Beam, 0.20% Link Outage, 27.2 MHz) (Multichannel Voice/Data)

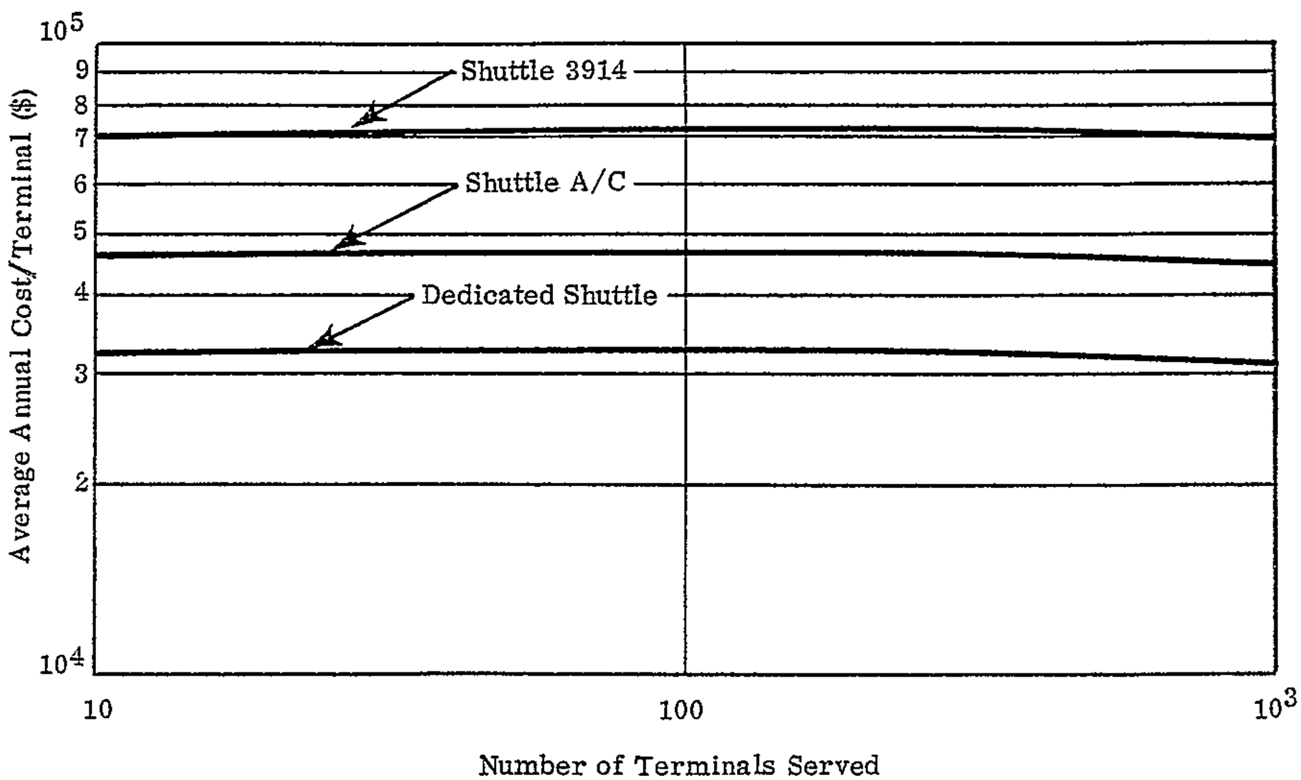

Figure 3-12. Average Annual Cost/Terminal vs. Number of Terminals Served (Ku-Band, 4 Beam, Satellite, 27.2 MHz Bandwidth, 0.20% Link Outage) (Multichannel Voice/Data)

agreement with the satellite power per channel curves. When the Dedicated Shuttle satellite is chosen, the terminal G/ T moves in the opposite direction to the satellite power/ channel. This is in agreement with the results observed for the "Voice/ Facsimile" service. It means that the link uplink-to-downlink C/ N ratio remains constant, as a consequence of the high cost of satellite power, but the terminal G/ T trades off with the satellite. In both cases mentioned above, the ground antenna diameter increases as the size of the network increases from 10^2 to 10^3 terminals, while the transmitter and receiver capability decrease.

When a four-beam Dedicated Shuttle satellite serves 10^2 terminals, the optimum terminal parameters are: (1) G/ T = 31.5 dB/°K, (2) EIRP = 61.3 dBW, (3) antenna diameter = 7.0 meters, (4) receiver noise temperature = 265° K, and (5) transmitter power = 2 watts. This is an autotracked Cassegrain antenna, an uncooled parametric amplifier or possibly GaAsFet receiver, and a GaAsFet solid-state transmitter.

Variations in the terminal parameters that increase system costs by no more than 10% are depicted in Table 3-17. The bounding parameters are read from the system optimization curves depicted in Appendix 4. The most effective way for relieving the terminal subsystem requirements, is to reduce the G/ T by 4.5 dB. When a four-beam Dedicated Shuttle satellite serves 10^2 terminals, the terminal parameters become: (1) G/ T = 27 dB/°K, (2) EIRP = 61.3 dBW, (3) antenna diameter = 4.5 meters, (4) receiver noise temperature = 350° K, and (5) transmitter power = 5.0 watts. This is a 14.5 foot Cassegrain antenna with a manual steering capability, a GaAsFet low noise receiver and a GaAsFet solid-state transmitter.

If the 7dB of satellite antenna advantage for the Southeast is eliminated another 2.5 dB of ground terminal, EIRP and G/ T capability can be eliminated. In this case, the above-ground terminal parameters become: (1) G/ T = 24.5 dB/°K, (2) EIRP = 58.8 dBW, (3) antenna diameter = 4.5 meters, (4) receiver noise temperature = 620° K, and (5) transmitter power = 3 watts. These requirements are deceptively modest; however, they do reflect the use of a high gain four-beam satellite antenna and a relatively modest link C/No requirement. On the other hand, they are somewhat distorted by the fact that the system optimization occurred on the flat cost portion of the satellite cost/performance curves. In this region, little cost saving is realized by reducing satellite power density. When the satellite channel bandwidth is appropriately widened, the optimum satellite power density will be somewhat lower and the terminal parameters higher.

The uplink-to-downlink ratios for this service are displayed on the system optimization curves in Appendix 4. A value of about 21 (i.e., 13.2 dB) results when a four-beam Dedicated Shuttle satellite serves a network of 10^2 terminals. This is a very high ratio and it reflects the fact that satellite power is very expensive for this service.

Table 3-17. Bounds on Ground Terminal Parameters (Ku-band, 4-Beam Satellite, 0.20% Outage, 10^2 Terminals, 27.2 MHz) (Multichannel Voice/Data)

Launch Vehicle	Terminal Parameter	Bound Reached By		Bound Reached By	
		G/T Reduction	EIRP Reduction	G/T Increase	EIRP Increase
Shuttle 3914	G/T(dB/°K)	29.0	33.0(1)	38.5	33.0(1)
	EIRP(dBW)	62.3(1)	60.3(2)	62.3(1)	80.3
	Antenna Dia. (Meters)	6.5	8.0	11.0	10.0
	Receiver Temp. (°K)	510	265	150	450
	Transmitter Power (Watts)	3.0	1.5	1.0	80
Dedicated Shuttle	G/T(dB/°K)	27.	31.5(1)	37.	31.5
	EIRP(dBW)	61.3(1)	60.3(2)	61.3(1)	75.3
	Antenna Dia. (Meters)	4.5	7.0	10.5	8.5
	Receiver Temp. (°K)	350	350	175	505
	Transmitter Power (Watts)	5.0	1.5	1.0	30

(1) Corresponds to optimum point.
(2) Corresponds to minimum EIRP available at optimum G/T point

6. Total System Cost Breakdown

Total system costs per terminal, including fixed performance items, are summarized in Table 3-18. The costs shown, when a Dedicated Shuttle satellite is selected, are $38,825 annually per terminal, $3,235 per month per terminal or $6,470 total per month on a full duplex basis. This breaks down to about $540 total per month per duplex voice channel or $6.00 total per two-way conversation if an average of 3 calls per voice channel are handled each day. The fixed items included in the table are entirely fixed equipment. No special operators are required. The fixed equipment capital cost is $25,558, based on a buy of 10 items per manufacturer per year (see Appendix 1 for a detailed breakdown of the fixed equipment cost). This converts to a $5,955 annual cost.

The major cost item for this service is the satellite. Fixed equipment costs are almost insignificant. The breakdown of costs between the satellite and earth terminals is further verified by the sensitivity analysis. Results of this analysis are displayed in Appendix 4. When a four-beam Dedicated Shuttle satellite serves 10^3 terminals, a 10 dB reduction of satellite costs results in a 72% decrease in total costs. A corresponding reduction of ground terminal costs results in a 29% decrease.

Although the above costs are reasonable, further cost reductions are possible. Wider satellite channel bandwidths applied to either a one-beam or four-beam FDMA satellite design can result in considerable cost reductions. Longer satellite lifetimes, higher satellite reliabilities, shuttle optimized designs, more efficient solar arrays, ion jets, etc. also can reduce costs. The application of multibeam satellite technology may be of benefit if network sizes of 10^3 to 10^5 terminals become a reality. As previously discussed, large network sizes make a channelized FDMA satellite a possibility. In addition, with a large network the unit cost of TDMA modems becomes small enough that a multibeam synchronous TDMA design has possibilities. The application of delta modulation can reduce data rates and link performance requirements, thereby resulting in additional savings.

E. VOICE/ FACSIMILE (TDMA)

1. Average Annual Cost Vs Number of Beams Per Satellite

Two different satellite channel burst rates (i.e., 40.12 Mbps and 60.112 Mbps) are considered for the TDMA version of the voice/ facsimile teleconferencing service. These correspond to channel bandwidths of about 30 MHz and 45 MHz when QPSK modulation and a BT product of 1.5 is used. In both cases, the satellite output power backoff is typically 0 dB for the TDMA approach to multiple access. Average annual costs/ terminal are compared in Table 3-19. As indicated, there is no cost advantage for either rate. This is in agreement with the results of the previous FDMA analysis (see Section 3.3.C), where both 15.68 MHz and 31.36 MHz satellite channel bandwidths are shown to produce equivalent cost results. The 40.12 Mbps burst rate is adopted for all further tradeoffs considerations. At this rate, the modem requirements are less stringent and the satellite channel power requirements are lower.

Table 3-18. Breakdown of Total Average Annual Cost/Terminal (Ku-Band, 4 Beam Satellite, 0.20% Link Outage, 10^2 Term., 27.2 MHz) (Multichannel Voice/Data)

Launch Vehicle	Total Average Annual Cost ($)	Percent of Cost In: Satellite	Ground Terminal	Fixed
Shuttle 3914	77,935	78.	14.	8.
Dedicated Shuttle	38,825	59.	26.	15.

Table 3-19. Average Annual Cost per Terminal vs Satellite Transponder Burst Rate (Ku-Band, 0.20% Outage) (Multi-channel Voice/Data)

Launch Vehicle	Burst Rate (Mbps)	1 Beam		4 Beams	
		10^2 Term.	10^4 Term.	10^2 Term.	10^4 Term.
Shuttle 3914	40.12	\$6.440	\$4.595	\$4.640	\$3.070
	60 112	6 465	4.595	4.665	3.085
Shuttle A/C	40.12	5.815	4.105	4,080	2,665
	60.112	5,825	4.105	4,100	2,670

2. Average Annual Cost Vs. Number of Beams Per Satellite

In a TDMA approach to the voice/facsimile service, a multibeam design can be implemented without suffering penalties as far as the efficiency of the satellite design is concerned. Extensive channelization to supply beam-to-beam interconnections is not required. The time sequential nature of the signalling allows a single satellite channel to be switched from beam-to-beam in synchronization with the TDMA frame format. Thereby, beam-to-beam connections are made on a temporal basis as needed. Further, since one wideband channel is used and terminal burst durations can be flexibly varied to handle different data rates, considerable statistical averaging takes place. The average annual costs associated with both one- and four-beam satellite systems are given in Table 3-20. The four-beam system is obviously less expensive. However, both are carried forward to give a thorough comparison of the two. The four-beam model used is the same one as employed for the FDMA satellite. It is believed to give a reasonable approximation of the four-beam TDMA satellite as long as the optimization occurs in the constant Δcost/Δpower region of the satellite performance/cost curves. Notice that even a TDMA satellite is likely to contain multiple channels since cost-effective modem technology is not available to handle individual channel burst rates of more than about 200 Mbps.

3. Satellite Requirements

The high satellite power densities observed for the FDMA version of this service are reconfirmed in Fig. 3-13. The basic trend of the power per channel curves is once again downward as the number of terminals increases and the size of the ground terminal buy increases. The figure shows that the number of satellite channels required increases from 0.02 to 0.2 to 1.9 as the number of terminals in the network increases from 10^2 to 10^3 to 10^4. This is a consequence of handling 312 signal accesses per satellite channel and employing a constant factor of 17 terminals per signal accessing the satellite (see Section 3.4.D for an operating scenario). The figure also shows that the satellite capacity requirements are reasonable over the entire range of network sizes under consideration. A Shuttle Atlas-Centaur satellite appears an excellent choice for serving a network of 10^3 to 10^4 terminals.

The satellite coordination limits are based on the four-beam satellite curve shown in Figure 3-5. No satellite output power backoff is considered and the channel bandwidth is approximately 27 MHz. Consequently:

$$P_{Coord} = P_{Curve}$$

4. Satellite and Ground Terminal Cost Vs Network Size

Average annual cost per user terminal for the satellite and ground terminal, excluding fixed equipment, is depicted in Figure 3-14. As expected, a steady downward

Table 3-20. Average Annual Cost per Terminal Vs. Number of Beams per Satellite (Ku-Band Satellite, 40.12 Mbps Burst Rate) (Voice/Facsimile, TDMA)

No. Beams	Launch Vehicle	0.20% Outage		0.1% Outage	
		10^2 Term.	10^4 Term.	10^2 Term.	10^4 Term.
1 Beam	Exp. 2914	7,100.	5,110.	8,835.	6,975.
	Exp. 3914	6,765.	4,856.	8,370.	6,630.
	Shuttle 3914	6,440.	4,595.	7,940.	6,320.
	Exp. A/C	6,095.	4,330.	7,440.	5,895.
	Shuttle A/C	5,815.	4,105.	7,035.	5,540.
	Ded. Shuttle	5,330.	3,720.	6,305.	4,930.
4 Beams	Exp. 2914	5,165.	3,480.	6,260.	4,555.
	Exp. 3914	4,840	3,225.	5,825.	4,200.
	Shuttle 3914	4,630.	3,070.	5,545.	3,975.
	Exp. A/C	4,250.	2,800.	5,035.	3,585.
	Shuttle A/C	4,080.	2,665.	4,815.	3,415.
	Ded. Shuttle	3,725.	3,410.	4,355.	3,045.

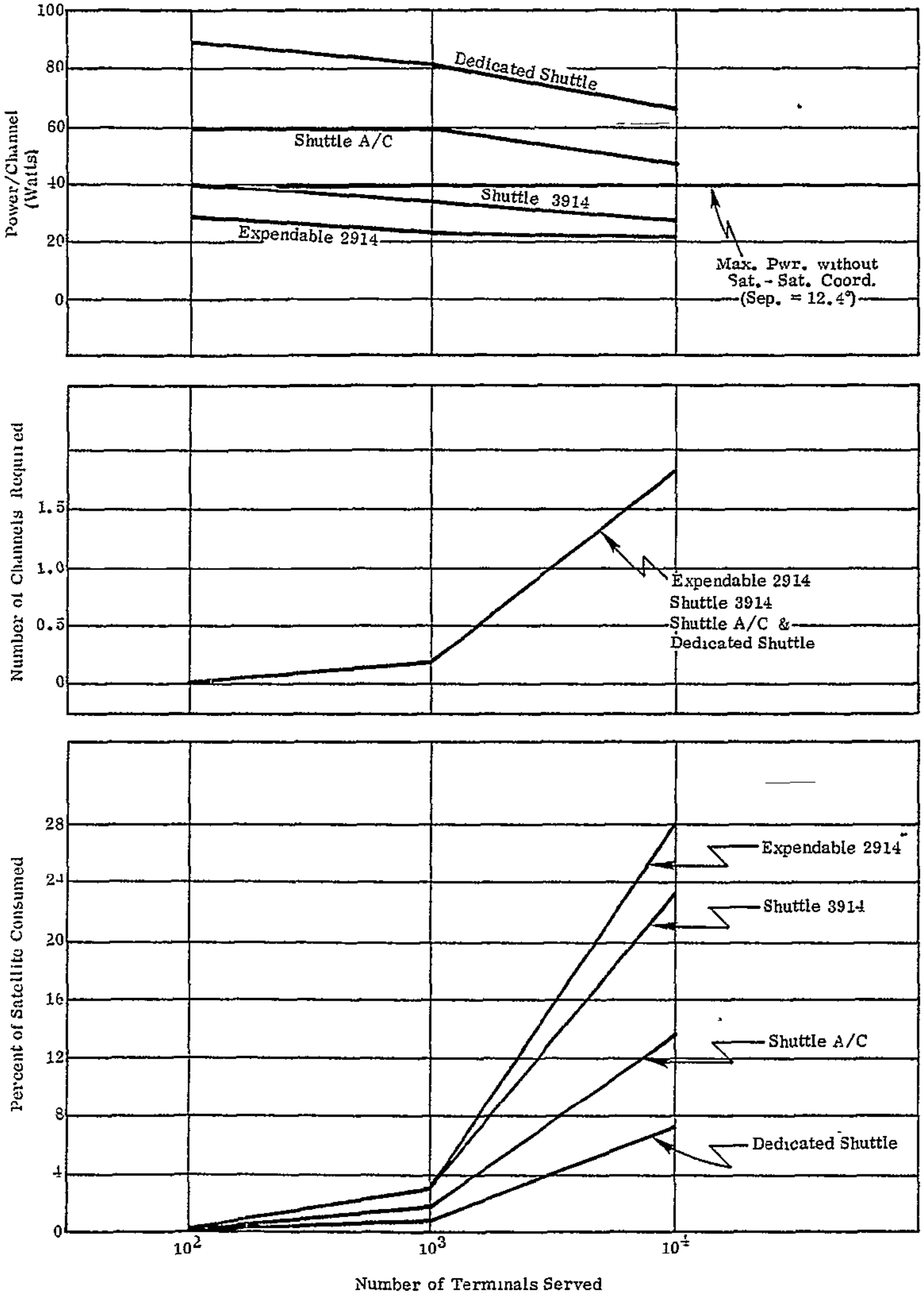

Figure 3-13. Satellite Power and Capacity Requirements
(Ku-Band, 4 Beam, 0.20% Link Outage, 40.12 Mbps)
(Voice/Facsimile, TDMA)

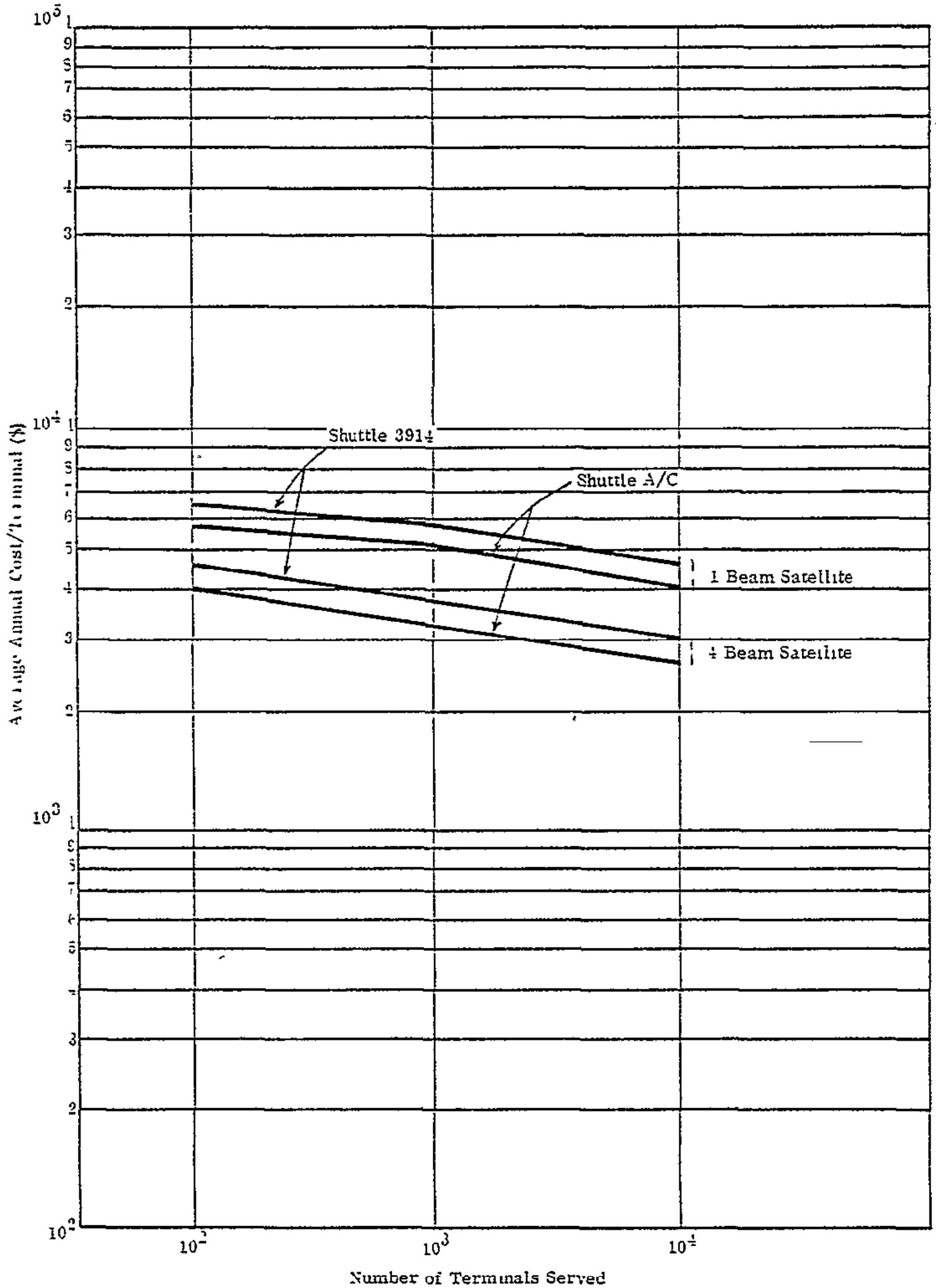

Figure 3-14 Average Annual Cost/Terminal vs. Network Size
(Ku-Band, 40.12 Mbps Burst Rate, 0.20% Link Outage)

cost trend exists as the size of the network and the ground terminal buy increases. The costs for the four-beam approach are considerably less expensive due to the extra satellite antenna gain. The average annual cost per terminal for a Shuttle Atlas-Centaur satellite serving a network of 10^4 terminals is seen to be about $2,700. This amounts to $26 per terminal per call or a total cost of about $52 per call since a full duplex capability is provided. This is based on each terminal handling an average of 104 calls annually (see Section 3.4D for the operating scenario associated with this service). These costs are considerably below those of the FDMA system as expected.

5. Ground Terminal Requirements

Curves depicting the trends in ground terminal G/T, EIRP, antenna diameter, receive system temperature, and transmitter power as a function of the number of terminals in the network are presented in Appendix 4. The terminal G/T variations are in the opposite direction to those observed in the satellite power/channel curves while the terminal EIRP variations track them. This is the same pattern that has been observed in a number of previous cases. The variations are accomplished entirely by changing transmitters and receivers. The antenna diameter remains constant regardless of the number of terminals in the network.

When a one beam Shuttle Atlas-Centaur satellite serves 10^4 terminals, the optimum terminal parameters are: (1) G/T = 25.5 db/°K, (2) EIRP = 59.3 dBW, (3) antenna diameter = 3.9 meters, (4) receiver noise temperature = 350°K, and (5) transmitter power = 4 watts. When a four beam Shuttle Atlas-Centaur satellite serves 10^4 terminals, the optimum terminal parameters are: (1) G/T = 23.5 dB/°K, (2) EIRP = 52.3 dBW, (3) antenna diameter = 3.5 meters, (4) receiver noise temperature = 450°K, and (5) transmitter power = 1 watt. Both of these terminals employ Cassegrain antennas with a manual steering capability, and GaAs FET low noise receivers. The FDMA system employs a GaAs FET solid state transmitter. The TDMA system uses an energy storage device that radiates in high power bursts. The TDMA power level indicated is the long term average level rather than the peak burst power. Costing of these tubes has been on an average power basis assuming the same costs as for a CW tube of the same average power level. This is considered to be an optimistic first order approximation.

Deviations in the terminal parameters that increase system costs by no more than 10% are depicted in Table 3-21. The bounding parameters are read from the system optimization curves depicted in Appendix 4. The most effective methods for relieving the terminal subsystem requirements is to reduce the G/T by 2 dB to 2.5 dB. The result is still a ground terminal of the type described above, however, the performance requirements are somewhat reduced. For instance, the terminal in the four beam satellite system uses an antenna having a diameter of only 3 meters. Further reductions can be realized if the 7 dB of satellite antenna gain advantage provided to the Southeast is eliminated.

The uplink-to-downlink C/N ratios for this service are displayed on the system optimization curves in Appendix 4. A value of 6 applies when a one beam Shuttle Atlas-Centaur satellite serves a network of 10^4 terminals. This compares with a value of 10 obtained in the corresponding FDMA version of this service. The reduction in the ratio is a result of eliminating the backoff and making satellite output power less expensive.

Table 3-21. Bounds on Ground Terminal Parameters (Ku-Band, Shuttle A/C, 0.20% Outage, 10^4 Terminals, 40.12 Mbps) (Voice/Facsimile, TDMA)

No. Beams/ Satellite	Terminal Parameter	Bound Reached By		Bound Reached By	
		G/T Reduction	EIRP Reduction	G/T Increase	EIRP Increase
1	G/T (dB/°K)	23.0	25.5(1)	28.5	25.5(1)
	EIRP (dBW)	59.3(1)	53.3	59.3(1)	65.3
	Antenna Dia. (Meters)	3.5	4.0	4.5	4.5
	Receiver Temp. (°K)	580	395	230	510
	Transmitter Power (Watts)	5.0	1.0	3.0	12.5
4	G/T (dB/°K)	20.5	23.5(1)	27.0	23.5(1)
	EIRP (dBW)	52.3(1)	47 3	52.3(1)	61.3
	Antenna Dia. (Meters)	3.0	3.5	4.5	3.5
	Receiver Temp. (°K)	745	510	350	510
	Transmitter Power (Watts)	1.5	0.3	0.6	8.0

Note: (1) Corresponds to Optimum Point

6.0 Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items, are summarized in Table 3-22. The costs shown, when a four beam shuttle Atlas-Centaur satellite is selected, are $22,460 annually per terminal and $215 per call per terminal. This means the total cost per two way call is about $430 which is well above the costs for the corresponding FDMA version of this service. The difficulty lies in the high cost of the TDMA modem. Perhaps as these modems become more common and are produced in higher volumes the prices will decrease to where they can be cost effective at modest data rates. However, it is highly unlikely that they will be a reasonable choice for a 100 Kbps service any time in the next decade. The modem costs are so dominant that choosing a smaller G/T earth terminal, causing a 10% increase in satellite/ground terminal costs, has a negligible impact on the numbers displayed in the table. The fixed equipment capital cost is $84,953 based on a buy of 10^3 items per manufacturer per year, (see Appendix 1 for a breakdown of the fixed equipment costs). This converts into a $19,795 annual cost. The options available for reducing the system costs were described in the previous consideration of the FDMA version of this service.

F. Mobile Radio

1. Calculations of the G/T Requirements

Since the threshold carrier-to-noise ratio is 10 dB (see Appendix 5.1.H.1) and a 6 dB C/N margin is required (to meet the CCIR Rec. 353-2); the overall noise budget must be such that a 16 dB C/N (within a 25 KHz satellite voice channel bandwidth) will be provided. It can be shown that the Ku-band earth terminal (see Section 3.3.F.7) provides Ku-band downlink and uplink carrier-to-noise ratios of at least 20 dB. If the sum of all other carrier-to-noise ratios (e.g. the carrier to interference ratio) are greater than 25 dB, then a UHF uplink or downlink carrier-to-noise-ratio of 19 dB will provide a total C/N of 15.9 dB. With this in mind, 19 dB was established as the requirement for both UHF links.

If there is one operating UHF channel per antenna feed and the spacecraft power is distributed over the channel bandwidth, BW, the EIRP per voice channel (EIRP/CH) can be computed from: EIRP/CH = (EIRP x 80.5)/(BWx3200) where EIRP is the total radiated power of the spacecraft, there are 3200 user accesses /80.5 MHz of spectrum, and BW is given in MHz. Table 3-23 shows the spacecraft EIRP/CH.

The mobile radio G/T required to meet the EIRP/CH requirements are shown in Table 3-24. These values are a result of a conventional link calculation. If voice activated single channel per carrier equipments are implemented, they can all be reduced by about 2.5 dB.

Table 3-22. Breakdown of Total Average Annual Cost/Terminal (Ku-Band, Shuttle A/C, 0.20% Link Outage, 40.12 Mbps Burst Rate, 10^4 Terminals) (Voice/Facsimile, TDMA)

Number Beams/ Satellite	Total Average Annual Cost ($)	Cost Per Terminal Per Call (1) ($)	Percent of Cost In:		
			Satellite	Ground Terminal	Fixed
1	23,900	230	4	13	83
4	22,460	215	2.5	9.5	88

Note: (1) Cost/Terminal/Call = $\frac{\text{Total Cost/Terminal/Year}}{\text{104 Calls/Year}}$

Table 3-23. Useful Spacecraft EIRP/CH.

				BW		(Pt) Ku (3)		(Pt) UHF (3)		Reduction Factor per Channel (2)		EIRP/Ch.	
	Antenna Diameter	Min. Antenna Gain	MPT (1)	Single Pol.	Dual Pol.	Single Pol.	Dual Pol.	Single Pol.	Dual Pol.	Single Pol.	Dual Pol.	Single Pol.	Dual Pol.
Launch Vehicle	feet	dB	KW	MHz	MHz	KW	KW	KW	KW	dB	dB	dBW	dBW
Dedicated Shuttle	210	48.3	5.2	2066	3099	1.2	1.6	3.5	3.0	49.1	50.9	34.6	32.2
Dedicated Shuttle	120	43.6	8.8	671	1066	0.4	0.6	7.5	7.3	44.3	46.0	38.0	36.2
Dedicated Shuttle	60	37.6	11.7	161	242	0.2	0.2	11.0	11.0	38.0	39.8	40.0	38.2
Dedicated Shuttle	30	31.6	11.7	80.5	161	0.2	0.2	11.0	11.0	35.0	38.0	43.0	40.0
A/C Shuttle	120	43.6	2.5	671	1066	0.4	0.6	1.8	1.6	44.3	46.0	31.8	29.6
A/C Shuttle	60	37.6	4.5	161	242	0.2	0.2	4.0	4.0	38.0	39.8	35.6	33.8
A/C Shuttle	30	31.6	5.0	80.5	161	0.2	0.2	4.5	4.5	35.0	38.0	33.1	30.1

Notes :

(1) - Total Useful Power (Including Backoff)

(2) - Reduction Factor = $\frac{BW}{80.5} \times 3200$

(3) - Total Useful Power at this Frequency

2. Mobile Radio Antenna Alternatives

The mobile radio EIRPs which are compatible with the spacecraft antennas are shown in Table 3-25. The cost and important performance characteristics of mobile radio antennas are shown in Table 3-26. Transmitter powers of 25 to 30 watts are standard for present land mobile radios. Thus, even the highest mobile radio EIRP requirement (i.e. 11.5 dBW) can be met with a 50 watt standard transmitter regardless of which mobile radio antenna is selected. With this in mind, the cost trade-offs have concentrated on the mobile radio G/T, the UHF satellite bandwidth allocations and the number of users in the system.

3. Mobile Radio Receiver Noise Temperature

Typical costs of available 450 MHz band, 25 watt, mobile radios range from $400 for a fixed frequency unit to $1,900 for a unit with eight selectable frequencies. This is based on procurement in quantities of 1 to 10. The typical cost of an 800 MHz band mobile radio with a frequency synthesizer is $2000 in quantities of 1 to 10. Thus a mobile radio with a frequency synthesizer (capable of synthesizing at least 48 distinct frequencies) will cost about the same as the current mobile radios with 8 distinct frequencies.

The cost of mobile radio receivers (which consist of preamplifier, down-converter and IF amplifier) range from $500 to $550. The results of the mobile radio vendor survey indicates the cost may drop by 30% for quantities of 100, 35% to 40% for quantities of 1,000, and 60% for quantities of 10,000. The results of an independent survey of UHF receive system noise temperature vs cost is shown in Section 3.6. It is indicated that a 2000°K UHF receiver costs $600 in quantities of 10. Further, it is shown that cost reductions for larger quantity procurements follow the same trend as indicated by the mobile radio manufacturers for their sets. Thus, the mobile radio receiver costs are determined from the costs depicted in Section 3.6.

Based on these factors, the cost of the mobile radios, minus the antenna and receiver, can be determined. They are shown in Table 3-27.

Table 3-27. Cost of the Mobile Radios*

Cost in Dollars for Quantities of					
10	10^2	10^3	10^4	10^5	10^6
1500	1050	800	600	480	400

*Not including receiver and antenna costs

Table 3-24. Mobile Radio G/T Required To Provide 19 dB Downlink C/N

	Antenna Diameter	Min. Antenna Gain	MPT(1)	BW		No. of Voice Channels		Max. No of Users (2)		S/C EIRP/CH		Mobile Radio G/T	
				Single Pol	Dual Pol	Single Pol	Dual Pol	Single Pol	Dual Pol	Single Pol	Dual Pol	Single Pol	Dual Pol
Launch Vehicle	feet	dB	KW	MHz	MHz	N	N	n	n	dBW	dBW	dB/^{o}K	dB/^{o}K
Dedicated Shuttle	210	48.3	5.2	2066	3099	82,126	123,190	4,106,334	6,159,502	34.6	32.2	-17.5	-15.1
Dedicated Shuttle	120	43.6	8.8	671	1006	26,673	39,990	1,333,664	1,999,502	38.0	36.2	-20.9	-19.1
Dedicated Shuttle	60	37.6	11.7	161	242	6,400	9,600	320,000	480,000	40.0	38.2	-22.9	-21.1
Dedicated Shuttle	30	31.6	11.7	80.5	161	3,200	6,400	160,000	320,000	43.0	40.0	-25.9	-22.9
A/C Shuttle	120	43.6	2.5	671	1006	26,673	39,990	1,333,664	1,999,502	31.8	29.6	-14.7	-12.5
A/C Shuttle	60	37.6	4.5	161	242	6,400	9,600	320,000	480,000	35.6	33.8	-18.5	-16.7
A/C Shuttle	30	31.6	4.0	80.5	161	3,200	6,400	160,000	320,000	33.1	30.1	-16.0	-13.0

Notes: (1) - Total useful power (including backoff)

(2) - The probability of call blockage is P = 0.01.
There are 50 frequency slots available in each user's transceiver.
BW/CH = 25 KHz and there are 3200 voice channels/80.5 MHz bandwidth
Each frequency slot is allocated for 50 users.
There is an average of 2 users/Unit Call (UC).

Table 3-26. Cost/Dominating Characteristics of the Mobile Radio Antennas

Antenna Type	Minimum Gain(2) (dB)	Dimensions (inches)	$ Cost in Quantities of				
			10^2	10^3	10^4	10^5	10^6
λ/4 Whip	-3.4(3)	4.3" High	20	15	13	11	9
Log Conical Spiral	-3.4	41" High and 15" Base Dia.	49	36	31	26	22
Curved-Crossed Dipole	-4.8	6" High and 13" Diameter	25	19	16	14	11
Switched Crossed Dipole / Folded Monopole	3.5	Overall 9" High and 8.4" Wide	50	37	32	26	22
Switched Multiple Antenna With Randome	8.0	30" High 50" Diameter	350	260	224	188	159
Radome Mounted UHF(1) Five Foot Parabolic Structure	16.0	35" High 60" Diameter	500	367	316	265	224
Four Foot Reflector(1)	17.0	30" High 50" Diameter	450	330	284	238	202

Notes: (1) Automatic azimuth tracking and manual elevation tracking is employed.
(2) - Elevation angles of 15° to 90° as well as the VSWR losses are considered.
(3) - Operation up to 50° elevation is followed.

Table 3-25. Required Mobile Radio EIRPs For Compatibility With Spacecraft Antenna Options

Launch Vehicle	Sat. Antenna Diameter (feet)	Min. Sat. Antenna Gain (dB)	Sat. Receive System Noise (^oK)	Sat. G/T ($dB/^oK$)	Required Mobile Radio EIRP (dBW)
Dedicated Shuttle	210	47.7	458	21.1	-5.2
Dedicated Shuttle	120	43.0	458	16.4	-0.5
Dedicated Shuttle	60	37.0	458	10.4	+5.5
Dedicated Shuttle	30	31.0	458	4.4	11.5
A/C Shuttle	120	43.0	458	16.4	-0.5
A/C Shuttle	60	37.0	458	10.4	5.5
A/C Shuttle	30	31.0	458	4.4	11.5

4. The Number of Users (or Bandwidth) vs. G/T

The G/T displayed in Table 3-24 assumes that all the available satellite bandwidth is used. The variation of G/T with satellite bandwidth (or the number of users) is shown in Appendix 4 for the satellite antenna alternatives of Table 3-24.

5. Mobile Radio G/T Vs Receiver Plus Antenna Cost

Using the UHF receiver cost/performance curve of Section 3.6 and the mobile radio antenna cost/performance data of Table 3-26, the lowest cost pairing of receivers and antennas producing a given G/T can be computed. The results of such an optimization are plotted in Figure 3-15.

6. The Mobile Radio Cost Per Year

Present mobile radio production quantities are about 10,000/year. Production methods and associated costs are expected to improve with increased volume.

a. When production is in quantities of 100,000 per year, the mobile radio costs in quantities of 10; 100; 1,000; 10,000 and 100,000 will correspond to the mobile radio costs of Figure 3-15 and Table 3-27 in quantities of 100; 1,000; 10,000; 100,000 and 1,000,000.

b. When the production is in quantities of 1,000,000/year, the mobile radio costs in quantities of 10; 100; 1,000 and 10,000 will correspond to the mobile radio costs of Figure 3-15 and Table 3-27 in quantities of 1,000; 10,000; 100,000 and 1,000,000.

Using the G/T versus satellite bandwidth curves of Appendix 4, Figure 3-15 and Table 3-27, the mobile radio costs per year, shown in Tables 3-28 and 3-29, can be developed. A sample calculation of the second entry in Table 3-28 is shown below:

a. Given:
   i. Shuttle Atlas Centaur satellite with 10 meter antenna
   ii. 20,000 system users
   iii. Mobile radio purchase quantities of 10, 10^2, 10^3

b. From the G/T versus satellite bandwidth curves of Appendix 4, the required mobile radio G/T is -25dB/°K.

c. From Figure 3-15, the mobile radio receiver plus antenna costs for a G/T of -25 dB/°K are $950, $650 and $510 for quantities of 10, 10^2 and 10^3, respectively.

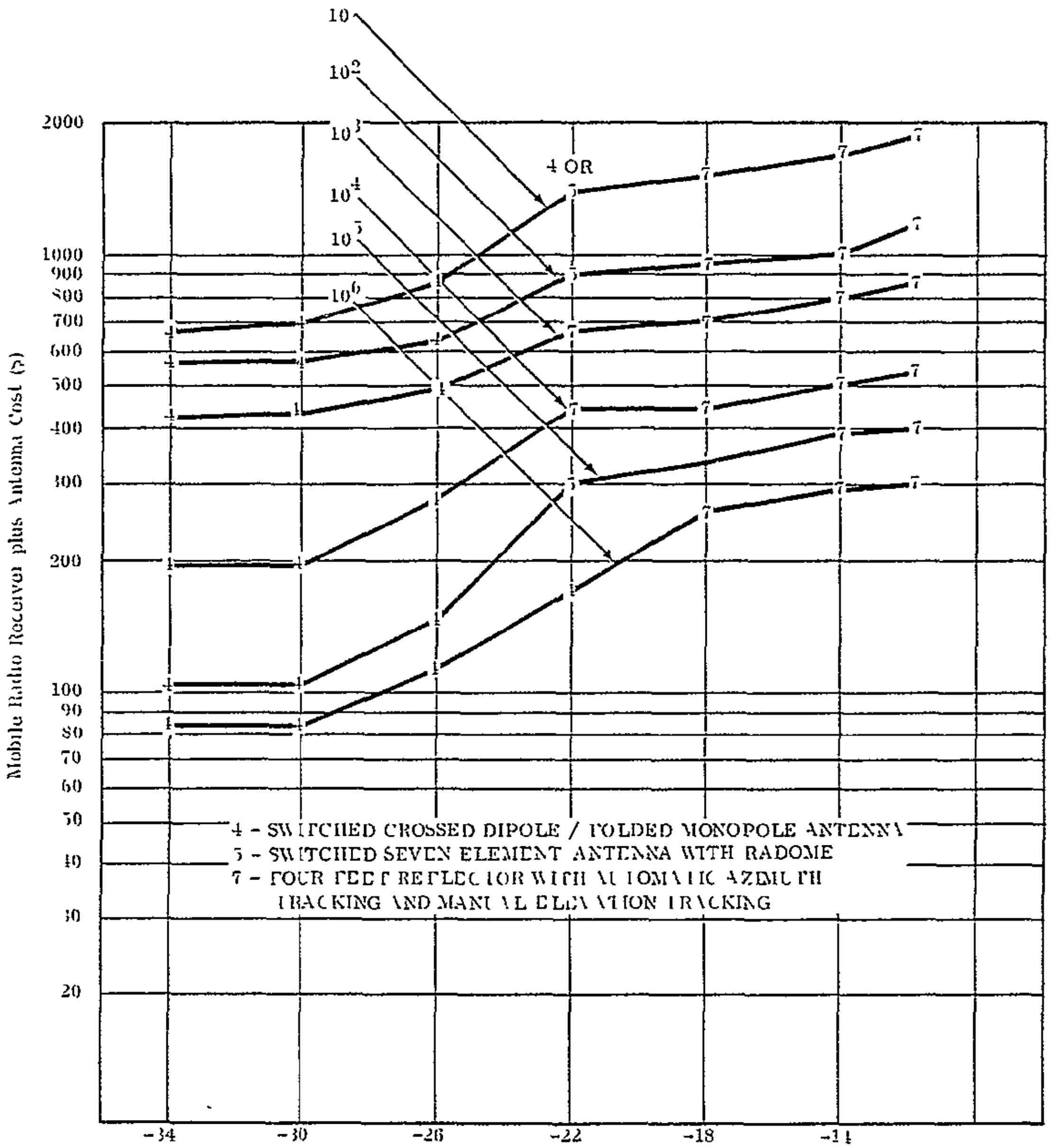

FIGURE 3-15. Mobile Radio Receiver Plus Antenna Cost vs. Mobile Radio G/T

Table 3-28. Mobile Radio Costs/Year (In Dollars)

Number of Users	Satellite Antenna Alternatives											
	A/C Shuttle 30' Ant.			Dedicated Shuttle 30' Ant.			A/C Shuttle 60' Ant.			Dedicated Shuttle 60' Ant.		
	Buy In Quantities of			Buy In Quantities of			Buy In Quantities of			Buy In Quantities of		
	10	10^2	10^3	10	10^2	10^3	10	10^2	10^3	10	10^2	10^3
10,000	524	382	291	499	375	284						
20,000	571	396	305	503	375	284	403	317	239	375	284	184
40,000	664	447	340	508	375	284	384	294	196	375	284	184
80,000	687	461	340	517	382	291	415	308	217	382	288	189
120,000	711	466	348	534	384	294	436	331	233	384	294	195
160,000	718	473	356	545	391	298	454	340	242	389	298	203
200,000	727	475	363	564	398	305	459	343	242	401	308	211
240,000	734	478	370	594	415	317	461	343	242	415	317	219
280,000	746	489	375	617	426	324	462	343	242	424	324	227
320,000	769	513	387	629	431	329	464	343	242	436	331	233
360,000							465	343	242	450	338	240
400,000							466	347	245	454	340	242
440,000							468	350	247	457	340	242
480,000							469	352	248	461	340	242
	$\underbrace{\qquad\qquad}_{\text{Lots of } 10^4}$			$\underbrace{\qquad\qquad}_{\text{Lots of } 10^4}$			$\underbrace{\qquad\qquad}_{\text{Lots of } 10^5}$			$\underbrace{\qquad\qquad}_{\text{Lots of } 10^5}$		

Table 3-29. Mobile Radio Costs/Year (In Dollars)

Number of Users	S/C Antenna Alternatives								
	A/C Shuttle 120' Antenna			Dedicated Shuttle 120' Antenna			Dedicated Shuttle 210' Antenna		
	Buy In Quantities of			Buy In Quantities of			Buy In Quantities of		
	10	10^2	10^3	10	10^2	10^3	10	10^2	10^3
80,000	382	294	196	375	284	185	375	284	185
160,000	419	319	221	375	284	185	375	284	185
240,000	450	336	242	380	284	191	375	284	185
320,000	454	336	242	384	294	198	380	289	190
400,000	457	336	242	387	298	202	384	293	196
480,000	458	336	242	394	303	206	385	295	197
630,000	463	336	242	415	317	219	298	203	146
930,000	473	356	249	445	336	238	315	217	157
1,130,000	475	361	254	452	340	242	326	226	165
1,333,664	478	368	256	457	340	242	340	242	182
1,680,000	490	377	261	459	340	242	340	242	184
1,999,502	524	391	270	461	340	242	340	242	186
3,000,000							340	242	189
4,106,334							345	246	191
5,100,000							356	249	195
6,159,502							363	254	197
	Lots of 10^5			Lots of 10^5			Lots of 10^6 After 480,000		

d. From Table 3-27, the mobile radio costs (excluding the receiver and antenna) are \$1,500 ; \$1,050; \$800 for quantities of 10, 10^2 and 10^3, respectively.

e. The sums of these costs are \$2450, \$1700 and \$1310 for quantities of 10, 10^2 and 10^3, respectively.

f. Annual costs, based on a 0.233 annualizing factor, are then \$571, \$396, and \$305 for the quantities of 10, 10^2 and 10^3 radios, respectively.

7. Telephone Network Interface Terminal Cost vs. Number of System Users

By spreading 100 earth stations over the lower 48 states, a 100-mile average coverage radius per station is achieved. This gives a maximum terrestrial tail of 100 miles and a terminal procurement quantity of 100.

A Ku-Band terminal, having a 83 dBW EIRP and a G/T of 31 dB/^{o}K, working with a satellite, having a 52 dBW EIRP, can provide 4 dB downlink and uplink rain margins. A 4 dB rain margin gives a satellite to earth link availability of better then 99.5%. From Section 3.5, it can be seen that the cost of the above terminal is \$85,000 in quantities of 100. These costs do not include the cost of channel units. Vendor cost estimates for channel units (CUs) are \$3,000 per CU, in quantities of 100. These costs are expected to drop by about 8% for each order of magnitude increase in quantity. Thus, the costs are \$3000, \$2760, \$2540 and \$2335 for quantities of 100, 1000, 10,000 and 100,000, respectively. To achieve the required call blockage factor and provide adequate redundancy, 100 CUs/terminal are supplied for each 3200 voice channels in the system. Thus when 3200 satellite voice channels are used, there is a total of 10,000 CUs in the system. From Table 3-24, it can be seen that there are 160,000 users per 3200 satellite voice channels. The number of CUs required per Ku-Band terminal is given by·

$$\frac{\text{No. of Users in the System}}{\text{160,000 Users}} \times 100 = \text{number of CUs}$$

With terminal and CU costs combined, the annual Ku-Band station costs vs. the number of system users are shown in Table 3-30. Note that these costs do not account for the variation in transmitter EIRP as the number of CUs increases. However, this represents a negligible factor in overall system costs.

8. Annual Cost of the Space Segment

The space segment annual costs are summarized in Table 3-31. The derivation of this data for the UHF land mobile satellite is described in detail in Appendix 2. When the space segment costs are allocated as a function of number of system users, the annual costs per user are as indicated in Table 3-32.

Table 3-30. Annual Ku-Band Terminal Costs Vs Number of System Users

Total Number of System Users	Number of CUs/ Earth Station	Cost of CUs/ Earth Station ($)	The Cost of 100 Earth Stations ($)	Annual Earth Station Costs/ User ($)
10,000	7	21,000	10,600,000	247
20,000	13	35,880	12,088,000	141
40,000	25	69,000	15,400,000	90
80,000	50	138,000	22,300,000	65
120,000	75	207,000	29,200,000	57
160,000	100	253,920	33,892,000	49
200,000	125	317,400	40,240,000	47
240,000	150	380,880	46,588,000	45
280,000	175	444,360	52,936,000	44
320,000	200	507,840	59,284,000	43
360,000	225	571,320	65,632,000	42
400,000	250	623,800	71,980,000	42
440,000	275	698,280	78,328,000	41
480,000	300	761,760	84,676,000	41
630,000	394	1,000,445	108,540,000	40
930,000	582	1,477,814	156,280,000	39
1,130,000	707	1,795,214	188,020,000	39
1,333,664	834	2,117,693	220,260,000	38
1,680,000	1,050	2,452,800	253,780,000	35
1,999,502	1,250	2,920,000	300,500,000	35
3,000,000	1,875	4,380,000	446,500,000	35
4,106,334	2,567	5,996,512	608,150,000	35
5,100,000	3,188	7,447,168	753,210,000	34
6,159,502	3,850	8,993,600	907,860,000	34

Table 3-31. Useful UHF Power for Land Mobile Service

Launch Vehicle	Antenna Diameter	MPT* (kW)	Space Segment Annual Cost
Dedicated Shuttle	(210')	5.2	$47.4M
Dedicated Shuttle	(120')	8.8	44.6
Dedicated Shuttle	(60')	11.7	42.4
Dedicated Shuttle	(30')	11.7	41.4
A/C Shuttle	(120')	2.5	33.3
A/C Shuttle	(60')	4.5	28.3
A/C Shuttle	(30')	5.0	27.3

* Total useful instantaneous power (including backoff but excluding activity factor).

Table 3-32. Annual Space Segment Cost/ User Vs. Number of Users

Total Number of System Users	Annual Space Segment Cost/User, $						
	Shuttle A/ G 30' Ant.	Dedicated Shuttle 30' Ant.	Shuttle A/ C 60' Ant.	Dedicated Shuttle 60' Ant.	Shuttle A/ C 120' Ant.	Dedicated Shuttle 120' Ant.	Dedicated Shuttle 210' Ant.
10,000	2730	4140	2830	4240	3330	4460	4740
20,000	1365	2070	1415	2120	1665	2230	2370
40,000	683	1035	708	1060	833	1115	1185
80,000	341	518	354	530	416	558	593
120,000	228	345	236	353	278	372	395
160,000	171	259	177	265	208	279	296
200,000	137	207	142	212	167	223	237
240,000	114	173	118	177	139	186	198
280,000	98	148	101	151	119	159	169
320,000	85	129	88	133	104	139	148
360,000			79	118	93	12	132
400,000			21	106	83	112	119
440,000			64	96	76	101	108
480,000			59	88	69	93	99
630,000					53	71	75
930,000					36	48	51
1,130,000					29	39	42
1,333,664					25	33	36
1,680,000					20	27	28
1,999,502					17	22	24
3,000,000							16
4,106,334							12
5,100,000							9
6,159,502							8

9. Annual Operating Cost

Given:

a. Five operators per earth station per 100 channel units.

b. 100 maintenance men to service the entire system, when the number of channel units/ earth station is 100 or less.

c. Two Communication Management Facilities (CMFs) for the system with 20 persons/ CMF.

d. Seven operators per earth station and 100 maintenance men for the entire system, when the number of CUs per earth station are between 100 and 500.

e. Eight operators per earth station and 150 maintenance men for the entire system, when the number of CUs per earth station are between 500 and 1000.

f. Nine operators per earth station and 150 maintenance men for the entire system, when the number of CUs per earth station are between 1000 and 4000.

The number of service personnel vs. channel units and their associated costs are shown in Table 3-33. An average annual salary per individual of $20K is employed in the table. When these costs are converted into annual cost as a function of total number of system users, the results are as indicated in Table 3-34.

Table 3-33. Annual Operating Cost Associated with the Land Mobile Satellite System

Number of CUs/ Ku-Band Terminal	Total No. of Service Personnel	Annual Operating Cost
7 to 100	640	12,800,000
100 to 500	840	16,800,000
500 to 1000	990	19,800,000
1000 to 4000	1140	22,800,000

10. Annual Cost Per User for Terrestrial Tails

Based on a 100-mile maximum distance/Ku-Band terminal, the average terrestrial tail should be about 30 miles. The cost per 30-mile terrestrial line is estimated to be $2,000 for 100 lines, $1,800 for 1000 lines, 1,620 for 10^4 lines and 1,460 for 10^5 lines.

Table 3-34. Annual Land Mobile Operating Cost Per User Vs the Number of System Users

Total Number of System Users	Annual Cost/ User ($)
10,000	1,280
20,000	640
40,000	320
80,000	160
120,000	107
160,000	80
200,000	80
240,000	70
280,000	60
320,000	53
360,000	47
400,000	42
440,000	38
480,000	35
630,000	27
930,000	21
1,130,000	18
1,333,664	15
1,680,000	14
1,999,502	11
3,000,000	8
4,106,334	6
5,100,000	4
6,159,502	4

Each CU is connected to a terrestrial line. Thus, the number of terrestrial lines is the same as the number of CUs. The required number of CUs per Ku-Band terminal were listed in Table 3-30. When the number of CUs is converted into the number of system users, the annual terrestrial tail cost per user is as listed in Table 3-35.

11. Annual Cost/ User of the Land Mobile Service

The annual costs per user of the "Land Mobile" service versus the number of system users are shown in Table 3-36. These costs represent the combination of the annual cost/ user for the mobile radios, the Ku-Band terminals, the space segment, operation and maintenance, and the terrestrial tail (see Tables 3-28, -29, -30, -32, -34 and -35). Mobile radio costs are based on buying in lots of 1000. Costs when radios are bought in lots of 10 and 100 are summarized in Appendix 4. Plots of the results when radios are bought in lots of 10 are also presented in Appendix 4.

12. Summary and Conclusions

The primary aim of the land mobile satellite communication study has been to outline the necessary guidelines and criteria required to achieve cost-effective service in the 1980s. Results and conclusions are as follows:

- Table 3-36 shows, when the number of system users are over 40,000, the Dedicated Shuttle costs range from about the same to somewhat less than the Shuttle Atlas-Centaur costs. However, the Dedicated Shuttle cases provide more prime power than the Shuttle A/ C alternatives. Thus, the required mobile radio G/ T is always less.
- When the 30-foot antenna Dedicated Shuttle is selected, a switched crossed dipole/folded monopole mobile radio antenna is used at all indicated G/Ts. It has overall dimensions of 9" high by 8.4" wide, and a minimum of 3.5 dB of antenna gain between the elevation angles of 15° and 90°. When this antenna is employed with a 355°K receive system, a G/T of -22 dB/$^{\circ}$K is realized. This G/T gives more than adequate link performance in all of the 30-foot antenna Dedicated Shuttle applications depicted in Table 3-36. It does this while introducing only minor increases in annual cost per user. Further, this land mobile receiver can be applied to any of the other Dedicated Shuttle configurations, using bigger satellite antennas and serving larger user networks, with only modest increases in the annual cost per user.

Table 3-35. The Annual Terrestrial Tail Cost per User in the System

Total Number of Users In The System	The Required Number of CUs Per Earth Station	The Annual Terrestrial Tail Cost Per User In The System
10,000	7	140
20,000	13	117
40,000	25	113
80,000	50	113
120,000	75	113
160,000	100	113
200,000	125	101
240,000	150	101
280,000	175	101
320,000	200	101
360,000	225	101
400,000	250	101
440,000	275	101
480,000	300	101
630,000	394	101
930,000	582	101
1,130,000	707	101
1,333,664	834	101
1,680,000	1,050	91
1,999,502	1,250	91
3,000,000	1,875	91
4,106,334	2,567	91
5,100,000	3,188	91
6,159,502	3,850	91

Table 3-36 Annual Cost/User of the Land Mobile Satellite System Vs. the Number of System Users

Total Number of Users in the System	S/C and Satellite Antenna Alternatives: A/C Shuttle 30' Antenna		Ded. Shuttle 30' Antenna		A/C Shuttle 60' Antenna		Ded. Shuttle 60' Antenna		A/C Shuttle 120' Antenna		Ded. Shuttle 120' Antenna		Ded. Shuttle 210' Antenna	
	Cost ($)	Mobile Ant. Type* & G/T (dB/°K	Cost ($)	Mobile Ant. Type* & G/T (dB/°K)	Cost ($)	Mobile Ant. Type* & G/T (dB/°K)	Cost ($)	Mobile Ant. Type* & G/T (dB/°K)	Cost ($)	Mobile Ant. Type* & G/T (dB/°K)	Cost ($)	Mobile Ant. Type* & G/T (dB/°K)	Cost ($)	Mobile Ant. Type* & G/T (dB/°K)
10,000	4,688	4,-28	6,091	4,-38										
20,000	2,568	4,-25	3,252	4,-35	2,551	4,-30 5	3,202	4,-35						
40,000	1,546	7,-22	1,812	4,-32	1,127	1,-27.5	1,767	4,-32						
80,000	1,019	7,-19	1,147	4,-29	909	4,-24.5	1,057	1,-29	950	4,-26.8	1,081	4,-33.2	1,116	4,-35
120,000	852	7,-17.2	016	1,-27.2	746	4,-22.7	825	4,-27						
160,000	769	7,-16	799	1,-26	661	7,-21 5	710	4,-26	692	4,-23 8	706	4,-30 2	723	4,-32
200,000	728	7,-15	740	4,-25	612	7,-20 5	651	4,-25						
210,000	700	7,-14	706	4,-24	576	7,-19.5	614	4,-21	597	7,-21.8	593	4,-28.2	599	4,-30
280,000	678	7,-13.5	677	4,-23.5	548	7,-19	583	4,-23.5						
320,000	669	7,-13	655	1,-23	527	7,-18 5	563	4,-23	543	7,-20.8	534	4,-27 2	543	4,-29
360,000					511	7,-17.9	548	7,-22.4						
400,000					501	7,-17.5	533	7,-22	510	7,-19.8	503	4,-26.2	500	4,-28
440,000					491	7,-17	518	7,-21 5						
480,000					481	7,-16.7	507	7,-21 2	488	7,-19	476	4,-25 1	473	4,-27 2
630,000									463	7,-17.8	458	4,-21 2	389	4,-26 2
930,000									416	7,-16.1	417	4,-22 5	369	4,-24.5
1,130,000									411	7,-15.3	439	7,21 7	365	4,-23.7
1,333,664									435	7,-14.6	429	7,-21	372	4,-23
1,680,000									421	7,-13.5	409	7,-19.9	352	5,-21.9
1,999,502									424	7,-12.8	401	7,-19.2	347	5,-21.2
3,000,000													339	5,-19.3
4,106,334													335	7,-17.4
5,100,000													333	7,-16 5
6,159,502													334	7,-15

* The Antenna Types are; 4 - switched crossed dipole/folded monopole, 5 - switched seven element antenna with radome; 7- four feet reflector with automatic azimuth tracking and manual elevation tracking. (See Table 3-26 for characteristics)

- Based on the above, the annual cost per user for the Dedicated Shuttle with a mobile radio having a G/T of -22 dB/°K and the simple antenna, can be computed. The results of these computations are shown in Table 3-37 and plotted in Appendix 4. Table 3-37 summarizes the annual cost per user for a land mobile satellite system having graceful growth potential. This system has the following advantages and characteristics:

a) A G/T of -22 dB/°K using a simple mobile radio antenna.

b) A cost-effective mobile radio compatible with system sizes ranging from 10^4 to about $4x10^6$ users.

c) A telephone network quality service, with a 1 out of 100 blockage in any busy hour.

d) Nationwide connection from any mobile location to any fixed or mobile location, and from any fixed location to any mobile location.

e) Complete privacy for all system users.

f) Supervisory, control and other signalling modes similar to those of the telephone network.

g) A choice of modulation techniques, FM commanding or QPSK adaptive delta modulation techniques allowing data services at rates up to 32 Kbps.

h) Billing and all supervisory, service and control functions automatically performed by the Ku-Band terminals in conjunction with the central monitoring facilities.

Table 3-37. Annual Cost/ User Vs No. of System Users
(A -22dB/°K G/T Mobile Radio is Used)

Number of System Users	Spacecraft Alternatives: Dedicated Shuttle, 30' Ant.	Dedicated Shuttle, 60' Ant.	Dedicated Shuttle, 120' Ant.	Dedicated Shuttle, 210' Ant.
10,000	6,457			
20,000	3,618	3,491		
40,000	2,208	2,056		
80,000	1,506	1,341	1,369	1,404
120,000	1,272	1,103		
160,000	1,151	980	994	1,011
200,000	1,085	913		
240,000	1,039	866	875	887
280,000	1,003	829		
320,000	976	803	809	818
360,000		781		
400,000		764	770	777
440,000		749		
480,000		738	743	749
630,000			722	623
930,000			682	592
1,130,000			670	580
1,333,664			660	570
1,680,000			640	548
1,999,502			632	541
3,000,000				530
4,106,334				524
5,100,000				
6,159,502				

3.4 Ku-BAND SYSTEM OPTIMIZATION ALGORITHM

A. BASIC EQUATIONS

The Ku-Band transmit/ receive system optimization is performed by minimizing the system cost while satisfying the link performance equation. A large number of combinations of ground terminal EIRP, satellite EIRP, and ground terminal G/T, meeting the link requirements, are systematically scanned and costed from a comprehensive data base. The lowest cost combination is selected as the optimum system. The range of combinations searched is constrained only by the satellites and low to moderate cost earth terminals projected to be available in the time frame through 1985. The searches are conducted in a computer. This allows a large number of system optimizations to be completed as a function of a wide variety of system options. The system options were generated by varying the size of the satellite, the number of satellite antenna beams, the bandwidth of the satellite channels, the link availability, the number of earth terminals served, and the frequency band employed. (See Section 3.1.B for a complete list.)

The link performance equation can be broken into an uplink and downlink equation. The uplink equation is: $C_s/N_s=(E_g/M_u)\,(C/4\pi Rf)^2(G_{su}/KT_s)$

where:

- C_s/N_s is the uplink carrier to noise density ratio at the satellite receiver
- E_g is the EIRP of the ground terminal
- M_u is the margin allowed on the uplink
- C is the speed of propagation of electromagnetic energy in a vacuum (i.e., $3\mathrm{x}10^8$ m/ sec.)
- R is the nominal range from the earth terminal to the satellite (i.e., 38,850.6 kilometers for a 25° elevation angle to a geosynchronous satellite)
- f is the uplink frequency of operation (i.e., 14GHz)
- G_{su} is the uplink gain of the satellite antenna
- K is Boltzman's constant (i.e., $1.3806\mathrm{x}10^{-23}$)
- T_s is the noise temperature of the satellite receiver

The downlink equation is:

$$(C_T/N_o)\ (\beta)=(P_{sc}B_SG_{SD}/LB_{SC}M_{BO})\left[\frac{C_S/N_S}{C_S/N_S+B_S}\right](C/4\pi Rf)^2(G_g/KT_gM_D)$$

where:

- C_T/N_o is the total link carrier to noise density ratio as measured at the ground terminal receiver
- $\beta = (C_s/N_s) / \left[(C_s/N_s)-(C_T/N_o)\right]$ and is the degradation to downlink performance due to the noise contribution made by the satellite receiver.
- P_{sc} is the maximum output power of the satellite channel (i.e., the TWTA output)
- B_S is the signal bandwidth required by a particular user service
- G_{SD} is the downlink gain of the satellite antenna
- L is the attenuation due to line loss between the TWTA and the antenna feed (i.e., 1.259)
- B_{SC} is the bandwidth of the satellite channel
- M_{BO} is the amount of TWTA output backoff to eliminate any significant degradation due to intermodulation components.
- $(C_s/N_s) / \left[(C_s/N_s)+B_S\right]$ is the factor determining the loss of useful satellite channel output power due to the noise of the satellite receiver
- f is the downlink frequency of operation (i.e., 12GHz)
- G_g is the gain of the ground antenna
- T_g is the noise temperature of the receiver
- M_D is the margin allowed on the downlink

The cost equation is:

$$C_{user}(\$)=(C_{SC}/N_{TA})(B_S/B_{SC})\ 2\left(B_{SC}MN_{cs}\right)^2 \Big/ \left[2\left(B_{SC}MN_{cs}\right)^2+B_S{}^2\right]$$

$$+(1/4)(C_{TNE}+C_{TSE}+C_{TC}+C_{TW})$$

where:

- C_{user}(\$) is the average annual cost of a user ground terminal and an appropriate portion of the satellite

- C_{SC} is the annual cost of a satellite channel as defined from the satellite channel output power versus cost curves

- N_{TA} is the average number of terminals associated with a single signal bandwidth allocation, B_S.

- M is the number of antenna beams in the satellite

- N_{cs} is the number of channels in the satellite

- $2(B_{SC}MN_{CS})^2 / \left[2(B_{SC}MN_{CS})^2 + B_S^2\right]$ is a factor inserted to eliminate the inflation of C_{SC} due to the "fill factor (see Section 3.7) over the satellite lifetime. It becomes effective only when M=1, N_{CS}=1 and $B_S = B_{SC}$. In such instances, it equals 1/1.5. In all other instances, it is approximately one.

- C_{TNE} is the annual cost of the terminal selected for the Northeastern U.S.

- C_{TSE} is the annual cost of the terminal selected for the Southeastern U.S.

- C_{TC} is the annual cost of the terminal selected for the Central U.S.

- C_{TW} is the annual cost of the terminal selected for the Western U.S.

B. GROUND TERMINAL COST PER AREA

Ground terminal costs are determined from data curves as a function of EIRP, G/T and size of the buy. They are uniquely determined for each of four areas of the country. Ground terminal EIRP and G/T values for only one area (e.g., the Northeast) are employed in the link equation. The G/T and EIRP values in other areas are determined by comparing link margin requirements and satellite antenna gains available in the other areas with the reference link. The equations are as follows:

$$\Delta(G/T)_{other} = (G_{SD} - M_D)_{REF} - (G_{SD} - M_D)_{other} \text{ and}$$

$$\Delta(E)_{g\ other} = (G_{SU} - M_U)_{REF} - (G_{SU} - M_U)_{other}$$

Therefore:

$$(G/T)_{other} = (G/T)_{REF} + \Delta(G/T)_{other}$$

and

$$(E_g)_{other} = (E_g)_{REF} + \Delta(E_g)_{other}$$

With the unique EIRP and G/T requirements per area determined, unique costing can be performed provided the size of the buy applicable in each area can be established. The basic premise is that the size of the buy will be less than the number of terminals served nationwide (i.e., N_{TNW}) even if all the terminals are identical. This is because of the competitive nature of the American economy and the fact that the number of terminals served is taken to be an end of satellite life number. As a result, several companies are likely to be in the business of producing/ marketing ground terminals and several buys will be made from each company in the process of building up the system. When all terminals are identical, or if the terminals of any single area are the same as those of any other area, the average size of the buy, N_B, is taken to be:

$$N_B = N_{TNW}/10$$

When terminals are unique for each area of the country, there is further fragmentation. If the EIRP and G/T requirements for a given area are different than those of any other area, the average size of the buy is taken to be:

$$N_B = N_{TNW}/10^2$$

A buy size of $N_{TNW}/10^2$ produces a higher cost per terminal than a buy size of $N_{TNW}/10$. As a result, it pays to be unique only if the EIRP and G/T requirements are sufficiently below those of the other areas to result in a lower cost per terminal even though the buy is smaller. The threshold differences necessary for this to be true are listed, as a function of N_{TNW}, as follows:

N_{TNW}	$\Delta G/T$ Thresholds
10	2.0dB
10^2	2.0dB
10^3	4.0dB
10^4	3.0dB
10^5	3.0dB

These thresholds were established by reviewing the ground terminal data base.

The result of this is that the initially computed $\Delta G/T$ values must be compared against each other and the thresholds listed above. If the difference of the $\Delta G/T$ is less than the threshold, it is cheaper to employ the larger $\Delta G/T$ in all areas and make a common buy. If the difference exceeds the threshold, the smaller $\Delta G/T$ is not adjusted and a unique buy is made. The computer makes all size-of-buy determinations based on the $\Delta G/T$ values alone. If an adjustment upward is made, both the $\Delta G/T$ and the ΔE_g of the smaller terminal are changed to those of the larger terminal. Computer printouts of G/T and E_g per area are based on the final adjusted values of $\Delta G/T$ and ΔE_g.

The procedure used by the computer in making the size-of-buy and terminal performance adjustment decisions, involves ordering the initially computed $\Delta G/T$s from the largest to the smallest. Note that the initial $\Delta G/T$ of the reference link is zero. The second largest $\Delta G/T$ is compared against the largest and adjustments made as necessary. The third largest is then compared against the adjusted second largest and adjustments made as necessary. Finally, the fourth largest $\Delta G/T$ is compared against the adjusted third largest and adjustments made as necessary.

The one overriding requirement on all size of buy decisions is that the size must be at least 10. Costing curves have not been developed for buy sizes less than 10. Further, buying in lots smaller than this is not likely.

C. SYSTEM PARAMETER SEARCH OPERATIONS/ BOUNDS

Each system cost/ performance optimization starts by incrementing earth terminal E_g values into the uplink performance equation until:

$$C_s/N_s > C_T/N_o$$

This C_s/N_s is then employed in the downlink equation. Values of P_{sc} are incremented into the downlink equation and it is solved for a G_g/T_g corresponding to each P_{sc}. Satellite (i.e., P_{sc}) costs and the cost of each area's ground terminal (i.e., E_g and G/T) are incremented into the cost equation. Costs per user are computed. The lowest cost combination is saved and a larger value of E_g is incremented into the uplink equation. The same process is repeated. The sequence stops when the maximum allowable value of E_g is reached. The minimum cost combinations, corresponding to all values of E_g, are then reviewed and a minimum of the minimums selected. This is the optimum system configuration.

The values of E_g are scanned over a range from 26.3dBW to 97.3dBW in 1dB increments. The lowest practically usable E_g is that making $C_s/N_s > C_T/N_o$ while providing values of P_{sc} and G_g/T_g that are inside their bounds. The allowable range of G_g/T_g is dependent on the E_g value selected. The ranges are defined as follows:

- $-5dB/°K \leq G_g/T_g \leq [15+(E_g-26.3)]$ dB/°K
  for $26.3dBW \leq E_g \leq 50.3dBW$
- $-5dB/°K \leq G_g/T_g \leq 39dB/°K$
  for $50.3dBW \leq E_g \leq 73.3dBW$
- $[-5dB/°K+)(E_g-73.3)] \leq G_g/T_g \leq 39dB/°K$
  for $73.3dBW \leq E_g \leq 97.3dBW$

The allowable range of P_{sc} is from -10dBW to the maximum available from a transmit/receive satellite launched on a booster of the particular size being considered. The launch vehicle options range from the Delta 2914 to the Dedicated Shuttle. (See Section 3.7.)

The earth terminal performance bounds represent those created by antenna diameters ranging from 2 feet to 30 feet, receive system noise temperatures ranging from 10,000°K to 100°K, and transmitter powers ranging from 0.1 watt to 5,000 watts. The listed performance bounds are those applicable to the reference link alone. The portion of this range actually used is determined by the link equation and the values incremented into P_{sc} in 0.5dB steps. The performance parameters, for areas other than the reference area, are allowed to spill over outside these bounds. Ground terminal cost versus out-of-bounds performance projections are made by expanding the bounds on the antenna, receiver and transmitter curves used in the earth terminal optimization (see Section 3.5). The expanded bounds reflect antenna diameters ranging from 1 foot to 115 feet, receive system noise temperatures ranging from 65°K to 20,000°K, and transmitter powers ranging from 0.025 watts to 25,000 watts. These expanded ground terminal subsystem bounds are used in generating both inbound cost versus performance data and out-of-bounds data. This insures smooth projections from inbound data points to out-of-bounds data points.

D. INPUT CONSTANTS TO EACH SYSTEM OPTIMIZATION

During any single system optimization run, the variables are P_{sc}, E_g and G_g/T_g in the link performance equation plus C_{SC}, N_{cs}, C_{TNE}, C_{TSE}, C_{TC} and C_{TW} in the cost equation. The performance and cost equation variables are related to each other by the satellite and earth terminal data curves (see Sections 3.5 and 3.7). The remaining parameters are fixed. The selection of these parameters is a function of choosing the service, the number of satellite beams, the link outage, and the number of users served nationwide.

Choosing a service defines the parameters indicated in Table 3-38. The basis for the table C_T/N_o and B_S values is given in Section 2.2. B_{CS} is chosen to have an upper bound on the order of 25 to 35 MHz. This is compatible with the bandwidths commonly employed in current commercial satellite systems. In cases where B_S is on the order of 25 to 35 MHz, B_{SC} is selected to be the same as B_S. For the narrower bandwidth services, a limited number of smaller satellite channel bandwidths are considered. The evaluations, as a function of B_{SC}, were not intended to be exhaustive. They are performed merely to give an indication of service cost sensitivity to variations

in the satellite channel bandwidth. M_{BO} is defined to be compatible with the ratio of B_{SC}/B_S under consideration. With one signal in a satellite channel, no inband intermodulation products are generated and the transponder TWTA can be operated at saturation. With two signals in a satellite channel, a limited number of intermodulation products fall inband requiring a 1.6dB output backoff to give sufficiently linear operation. With three or more equally spaced signals in a satellite channel, the intermodulation problem reaches its worst and a 5.1dB backoff is required. The ground terminal configuration (i.e., redundant or nonredundant) is defined for each service in order to select the appropriate ground terminal cost/performance curves. The type of baseband signal (i.e., analog or digital) is defined in order to select the appropriate link margin versus outage tabulation.

Table 3-38. Service Related Performance/Cost Parameter Selections

Service	C_T/N_o(dB)	B_s(Hz)	B_{sc}(Hz)	Back-off(dB)	Configuration	Signal
Point-to-Point TV	85.2	22×10^6	22×10^6	0	Non-redundant	Analog
Compressed Bandwith T/V Facsimile	73.5	12×10^6	12×10^6	0	Non-redundant	Digital
			24×10^6	1.6		
			36×10^6	5.1		
Voice/ Facsimile (FDMA)	62.0	140×10^3	1.96×10^6	5.1	Non-redundant	Digital
			7.84×10^6	5.1		
			15.68×10^6	5.1		
			31.36×10^6	5.1		
Multichannel Voice Data	64.6	1.7×10^6	1.7×10^6	0	Redundant	Digital
			3.4×10^6	1.6		
			13.6×10^6	5.1		
			27.2×10^6	5.1		
Voice/ Facsimile (TDMA)	62.0	64×10^3	20.06×10^6	0	Non-redundant	Digital
			30.056×10^6			

Choosing the number of satellite beams (i.e., 1 or 4) provides a direct input to the cost equation, selects the appropriate set of satellite cost/performance curves, and selects the proper uplink and downlink satellite antenna gains. The satellite uplink and downlink antenna gains employed are defined in Table 3-39..

Choosing the link outage selects the uplink and downlink margins to be employed. These margins are listed in Tables 3-40 and 3-41. The listed margins are determined by the propagation losses (see Section 2.5) and the approach used to establish link performance requirements. The propagation losses include rain attenuation and the increase in receive system noise temperature that it introduces. A 1000°K satellite receive system and a 200°K ground terminal receive system were taken as typical of the technology applicable. Both clear sky and minimum acceptable performance levels are stipulated. The latter is the level that must be maintained for a very high percentage of the time (e.g., 99.9%) even in the presence of rain attenuation. It is to this level that rain margin is applied. It is rain margin that is a function of the link outage allowed. The clear sky requirement is established at a fixed level. This level is 7dB above the minimum performance level in the case of analog signals. It is 4dB above the minimum when digital signals are considered. The difference between minimum performance and what may be considered high performance is less for digital signals than for analog signals. The result of all this is to establish a minimum link margin of 7dB for analog signals and 4dB for digital signals. These minimum margins are reflected in Tables 3-40 and 3-41.

Choosing the number of users served nationwide, N_{TNW}, establishes the number of signals accessing the satellite, N_{SA}, and the average number of terminals associated with each access, N_{TA}. The values of N_{TNW}, N_{SA} and N_{TA} employed, as a function of the service selected, are listed in Table 3-42. Each listing reflects the operating scenario associated with that particular service. The operating scenario determines the N_{TA}. With N_{TA} essentially constant as a function of N_{TNW}, N_{SA} varies directly with changes in N_{TNW}. One additional constraint on N_{SA} is that it must be an even number when a full duplex service is under consideration. Point-to-Point TV is the only half duplex service considered.

Table 3-42. Ground Complex/Satellite Channel Access Pairing

	Point-to-Point TV		Compressed BW TV/Fax.		Voice/Fax.		Multichannel Voice/Data	
N_{TNW}	N_{TA}	N_{SA}	N_{TA}	N_{SA}	N_{TA}	N_{SA}	N_{TA}	N_{SA}
10	10	1	4	4	--	--	1	10
10^2	25	4	4	24	17	6	1	100
10^3	25	40	4	250	17	58	1	1000
10^4	--	--	--	--	17	588	--	--
10^5	--	--	--	--	17	5882	--	--

The N_{TA} of 25, employed for Point-to-Point TV, is based on a medical diagnostic service. The expectation is that the average duration of each medical diagnosis will be 30 minutes. Further, it is estimated that operation will be maintained 12 hours per day, 6 days per week. This amounts to a maximum of 144 calls per week. The diagnostic service modeled is one involving highly trained and skilled specialists

Table 3-39. Satellite Antenna Gains (Ku-Band)

Location	Uplink		Downlink	
	1 Beam	4 Beams	1 Beam	4 Beams
West	26.3	36.8	25.0	35.5
Central	26.3	36.8	25.0	35.5
South East	33.3	38.8	32.0	37.5
North East	26.3	31.8	25.0	30.5

Table 3-40. Link Margin (M_U) vs. Outage for 14GHz Uplink

Location / Sig. / Outage	WEST		CENTRAL		SOUTHEAST		NORTHEAST	
	Analog	Digital	Analog	Digital	Analog	Digital	Analog	Digital
1.0%	7	4	7	4	7	6	7	4
0.75%	7	4	7	4	7	7	7	4
0.5%	7	4	7	4	8	8	7	4
0.25%	7	4	7	4.5	11	11	7	4.5
0.1%	7	4	7	7	16	16	7	7.4
0.075%	7	4	8	8	18.5	18.5	9.0	9.0
0.05%	7	4	9.5	9.5	22	22	11.5	11.5
0.025%	7	4	13	13	29.5	29.5	16	16
0.01%	7.5	7.5	20.5	20.5	48	48	25.5	25.5

Table 3-41. Link Margins (M_D) vs. Outage for 12GHz Downlink

Location / Sig. / Outage	WEST		CENTRAL		SOUTHEAST		NORTHEAST	
	Analog	Digital	Analog	Digital	Analog	Digital	Analog	Digital
1.0%	7	4	7	4	7	4	7	4
0.75%	7	4	7	4	7	4	7	4.5
0.5%	7	4	7	4	7	4	7	5
0.25%	7	4	7	4	7	7	7	5.5
0.1%	7	4	7	6.5	13.5	13.5	7.5	7.5
0.075%	7	4	8	8.0	16	16	9.0	9
0.05%	7	4	10	10	20	20	11	11
0.025%	7	5	13.5	13.5	28	28	15.5	15.5
0.01%	8.5	8.5	20	20	45	45	25	25

at big city and university hospitals communicating with general practicioners and technicians in rural towns and hospitals. The service is scheduled on a week-to-week basis with a modest reserve capacity maintained for emergencies. Therefore, a relatively high average channel utilization rate of 50% can be adopted. This means 72 calls per week can be handled over each signal access allocation available in the satellite. If each terminal places an average of three-calls-per-week, there are 24 rural terminals plus one urban terminal associated with each satellite access.

The N_{TA} of 4, employed for Compressed Bandwidth TV/Facsimile, is based on its configuration as a mobile teleconferencing service. One or more trucks or vans operate within a metropolitan area. The TV equipment is transported to a conference room within the user's facility. One or two trained people are responsible for setting up the video/ audio equipment, aligning and setting up a satellite ground station, establishing links between the conference room and the ground station, and operating the video equipment during the conference. It is estimated that the average duration of a business conference is 1.5 hours. Assume 12 hours per day of operation over 5 1/ 2 days per week. A full duplex service is supplied. It is semi-scheduled with access being reserved about a week in advance. As a result, a relatively high channel utilization rate of 50% will be adopted. This means a pair of satellite accesses can handle about 22 calls per week. It is expected that each mobile terminal will handle an average of one-call per day or 5.5 calls per week. There are two terminals associated with each duplex circuit, therefore, there is an average of four terminals associated with each satellite access.

The N_{TA} of 17, employed for voice/ facsimile teleconferencing is based on a fixed installation of the ground terminal at each user's facility. Full duplex service is supplied. The average duration of a business conference is estimated to be one hour. Assume 12 hours per day of operation over 5 1/ 2 days per week. This service is semi-scheduled with accesses being reserved a few days in advance. Accordingly, a 50% channel utilization factor is adopted. This means a pair of satellite accesses can handle 33 calls per week. It is expected that each ground terminal will participate in an average of two teleconferences per week. As a result, an average of about 17 terminals are associated with each satellite access.

An $N_{TA} = 1$, established for multi-channel voice/ data, is based on it being a dedicated full duplex trunking service. However, in any of the three previous services, an N_{TA} anywhere within the range of 5 to 25 could be applied and justified, dependent on the operating scenario. N_{TA} is an important factor in the satellite/ ground terminal cost/ performance tradeoff. In most cases, its accurate determination requires considerable study involving an operating demonstration of the service and surveys of user expectations.

E. COMPUTED OUTPUTS AT EACH SYSTEM OPTIMIZATION

The computer outputs supplied, for the minimum cost point determined from each system optimization run, are as follows:

Annual Cost per User	$	xxx
Power per Satellite Channel (Watts)		xxx
Number Satellite Channels Required		xx
Percentage of Satellite Consumed		xx
Annual Satellite Cost per User		xxx

	G/T	EIRP	Cost/ User	Delta G/T	Sys Temp (dB)	Rcvr Temp (°K)	Ant. Dia.	Xmit Pwr. (W)	Pro-cure-ment
West	xx	xx	xxxx	xx	xx	xx	xx	xx	xx
Central	xx	xx	xxxx	xx	xx	xx	xx	xx	xx
Southeast	xx	xx	xxxx	xx	xx	xx	xx	xx	xx
Northeast	xx	xx	xxxx	xx	xx	xx	xx	xx	xx

where:

- Annual cost per user is the average annual cost of the satellite and ground terminal at the satellite power, earth terminal G/T and earth terminal EIRP giving the absolute minimum cost.

- Power per satellite channel (watts) is the output of a single satellite TWTA at the minimum cost point.

- Number of satellite channels required, N_{SC}, is determined as follows:

  $$N_{SC} = (N_{SA} \times B_S)/B_{SC}$$

- Percentage of satellite consumed, % SC, is determined as follows:

  $\% SC = N_{SC}/MN_{cs} \times 100$ where N_{cs} was previously defined as the number of channels in the satellite.

- Annual satellite cost per user, C_{SAU}, is determined as follows:

  $$C_{SAU} = \left(C_{SC}/N_{TA}\right)\left(B_S/B_{SC}\right) 2\left[B_{SC} MN_{cs}\right]^3 \Big/ \left(2\left[B_{SC} MN_{cs}\right]^2 - B_S^2\right)$$

- G/T is the optimum terminal's receive system figure of merit. Separate listings are made for four areas of the country.

- EIRP is the optimum terminal's radiated power. Again, separate listings are made for each area of the country.

- Cost per user is the annual cost of the optimum terminal in each area of the country.

- Delta G/T represents the adjustments made relative to the reference link (i.e., the Northeast) to determine the receive system figure of merit in each area of the country. The values displayed include the results of deciding whether a less costly terminal can be provided by adjusting the G/T and EIRP to those of a larger terminal in another area. This saves costs by allowing a common and therefore larger buy. Such common buy adjustments can occasionally result in a positive delta G/T on the Northeast link.

- System Temperature (dB), T_S, is the performance of the most cost-effective receive system for the listed G/T. It is determined from the earth station optimization algorithm (see Section 3.5).

- RCVR Temperature, T_R, is the determined as follows:

  $$T_R = 10^{(T_S/10)} - 50$$

  where T_R is given in $^{\circ}$Kelvin. The noise contribution due to rain attenuation is handled by increasing the link margin required (See Table 3-41.)

- ANT. Dia. is the diameter of the most cost-effective antenna for the listed G/T. The gain of this antenna is determined from the earth station optimization algorithm (see Section 3.5). This gain in dB, G, is converted into an antenna diameter through the use of the following equation.

  $$D = C \times 10^{(G/20)} / f\pi\sqrt{\eta}$$

  with $\eta = 0.65$ for $D \geq 8$ ft and $\eta = 0.5$ for $D < 8$ ft.

- XMIT PWR (W) is the power output of the most cost-effective transmit amplifier for the listed EIRP. The output power of this amplifier in dBW is determined from the earth station optimization algorithm (see Section 3.5). The power is converted into watts for printout.

- PROCUREMENT is the size of buy applicable in each area. It reflects the result of lumping slightly different ground terminals for separate areas together to increase the size of the buy. It indicates the set of ground terminal cost and procurement curves used in making the cost estimate.

F. SENSITIVITY ANALYSIS

The sensitivity analysis is performed by manipulating the basic link performance and system cost equations. Multiplying the uplink equation by 10 and 0.1 evaluates the impact of a +10dB and -10dB variation in ground transmitter performance with cost constant. Multiplying the downlink equation by 10 and 0.1 evaluates the impact of a -10dB and -10dB variation in either satellite transmitter or ground receiver performance with cost constant. Multiplying the satellite costs, in the cost per user equation, by 10 and 0.1 evaluates the impact of a variation in satellite costs with performance constant. A comparable operation on the ground terminal portion of the cost equation evaluates the impact of a variation in ground terminal costs with performance constant. With any of these variations instituted, a complete system optimization can be performed giving printouts of optimum system cost and satellite/ ground terminal configuration. The analysis can be completed with any of the basic system options (i.e., service, launch vehicle, link outage, number of terminals nationwide, number of beams per satellite, and bandwidth per satellite channel) selected.

3.5 EARTH STATION TRADEOFFS/ OPTIMIZATION ALGORITHM

A. PERFORMANCE VERSUS COST

Comprehensive Ku-Band earth station performance/ cost tradeoffs have produced optimized configurations ranging in cost from less than \$2K for a low performance transmit/ receive station to almost \$250K for a high performance station. The \$2K station provides nonredundant transmitters and receivers. It must be produced in average quantities of 10^5 per year per manufacturer. It includes a 3-foot antenna (i.e., fixed prime focus fed parabolic reflector), approximately 10,000 $^{\circ}$K receive system (i.e., diode mixer), and less than 100 milliwatt (i.e., GaAsFET solid-state) transmitter. This corresponds to an EIRP of 26.3dBW and a G/ T of -5dB/ °K. The \$250K station provides redundant transmitters/ receivers and is produced in average quantities of only 10 per year per manufacturer. It includes approximately a 40-foot antenna (i.e., autotracked Cassegrain), 250° K receive system (i.e., uncooled paramp), and a 2KW (i.e., klystron) transmitter. Throughout most of the performance range, the transmitter costs tended to be the driving force in the tradeoffs. The only exceptions were cases where a high G/ T (e.g., 30db/ °K) requirement is paired with a low EIRP requirement (e.g., 55dBW). However, the latter is a situation that is quite often realized in practice.

The optimizations consisted of selecting the lowest cost configuration from all feasible combinations of antennas, receivers and transmitters meeting a given EIRP and G/ T requirement. These optimizations are sequentially performed with EIRP and G/ T varied in incremental steps over the entire range of values of interest. Both redundant and nonredundant versions of Ku-Band earth stations procured in lots of 10, 10^2 10^3, 10^4 and 10^5 per year per manufacturer have been examined. This amounts to 10 sets of EIRP versus G/ T versus cost curves. Within each set, EIRP is examined over a range from 26.3 dBW to 97.3dBW and G/ T over a range from -5dB/ °K to 39dB/ °K. The full

set of performance versus cost data obtained is displayed in Appendix 4. Representative examples are displayed in Figures 3-16, -17, and -18.

The overall EIRP and G/T bounds are set based on the range of capabilities available from antennas between 2 feet and 30 feet in diameter, receive system temperatures between 10,000°K and 100°K, and transmitter powers between 100 milliwatts and 5KW. These subsystem constraints result in G/T bounds that do not extend over the whole range when EIRP is low (e.g., 26.3dBW) or high (e.g., 96.3dBW). The figures display these restricted bounds. The reason for the restriction is the constraint placed on antenna size by the EIRP requirement. When EIRP is low, a small antenna must be chosen even if a 100-milliwatt transmitter is used. Likewise, when EIRP is high, a large antenna must be used even if a 5KW transmitter is selected. The full range of G/T (i.e., 5dB/°K to 39dB/°K) is available only for EIRPs from 50.3dBW to 73.3dBW inclusive. (See Section 3.4C for a precise definition of the bounds.)

The figures clearly show that EIRP and the transmitter can be important factors in the terminal's cost. This is reflected in the surprisingly flat trend of the constant EIRP (i.e., Eg) curves. Compare this with the wide cost variation when a constant G/T is selected (e.g., with G/T = -5dB/°K, in Figure 3-16, the cost swings from $5K to $50K as Eg goes from 26.3dBW to 68.3dBW). At low values of constant Eg, the curves remain relatively flat with variation in G/T until the upper bound on the latter is approached. Table 3-43, at Eg = 40.3dBW, shows that transmitter performance decreases as antenna and receiver performance increase along with G/T. The flat portion of the curve is where transmitter cost decreases cancel out antenna and receiver cost increases. Obviously, with the Eg requirement so modest, a point is reached where antenna and receiver costs dominate. At intermediate values of Eg, a U-shaped cost trend as a function of variation in G/T is observed. Table 3-43 at Eg = 68.3dBW, indicates the same kind of transmitter cost versus antenna and receiver cost tradeoff observed above. However, in this case, the higher Eg requirement is producing a much more costly transmitter. As a result, the transmitter cost dominates at low values of G/T where antenna size is forced to be small and receiver temperature high. As G/T increases allow the antenna size to increase, the transmitter power decreases until its cost becomes small relative to the magnified antenna/receiver costs. At high values of constant Eg, the transmitter power and cost requirements remain high over the entire range of variation of G/T (see Table 3-43, Eg = 89.3dBW). Consequently, the cost trend is relatively flat over the entire range.

Data like that shown in Table 3-43 has been produced in 1dB increments of E_g and G/T over the entire range within the bounds discussed above. It also encompasses all of the redundancy and size of buy options indicated above. A corresponding ground terminal cost is developed for each point. This is all accomplished in a computer and is an input to the system optimization algorithm described in Section 3.4. In some cases, the table indicates antennas, receivers, and transmitters falling slightly outside the range of capabilities defined above in establishing E_g and G/T bounds. This is a result of projecting the subsystem data used in the system optimization outside the preliminary bounds. Antenna sizes are allowed to range from 1 foot to 115 feet, receive

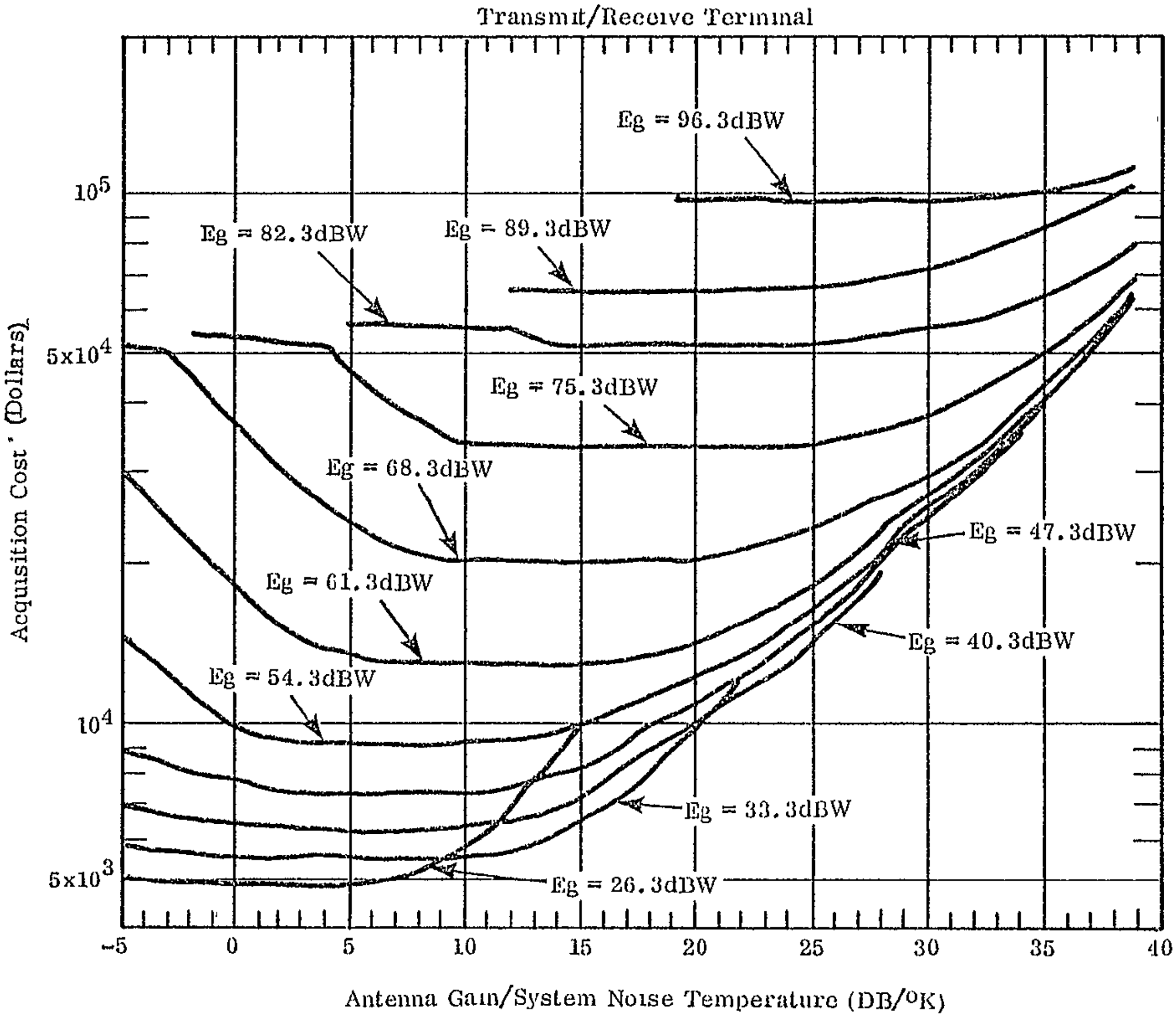

Figure 3-16. Ground Terminal Cost Vs. G/T Vs. EIRP (Eg)
(Ku-Band, Non-Redundant, 100 Units Procured)

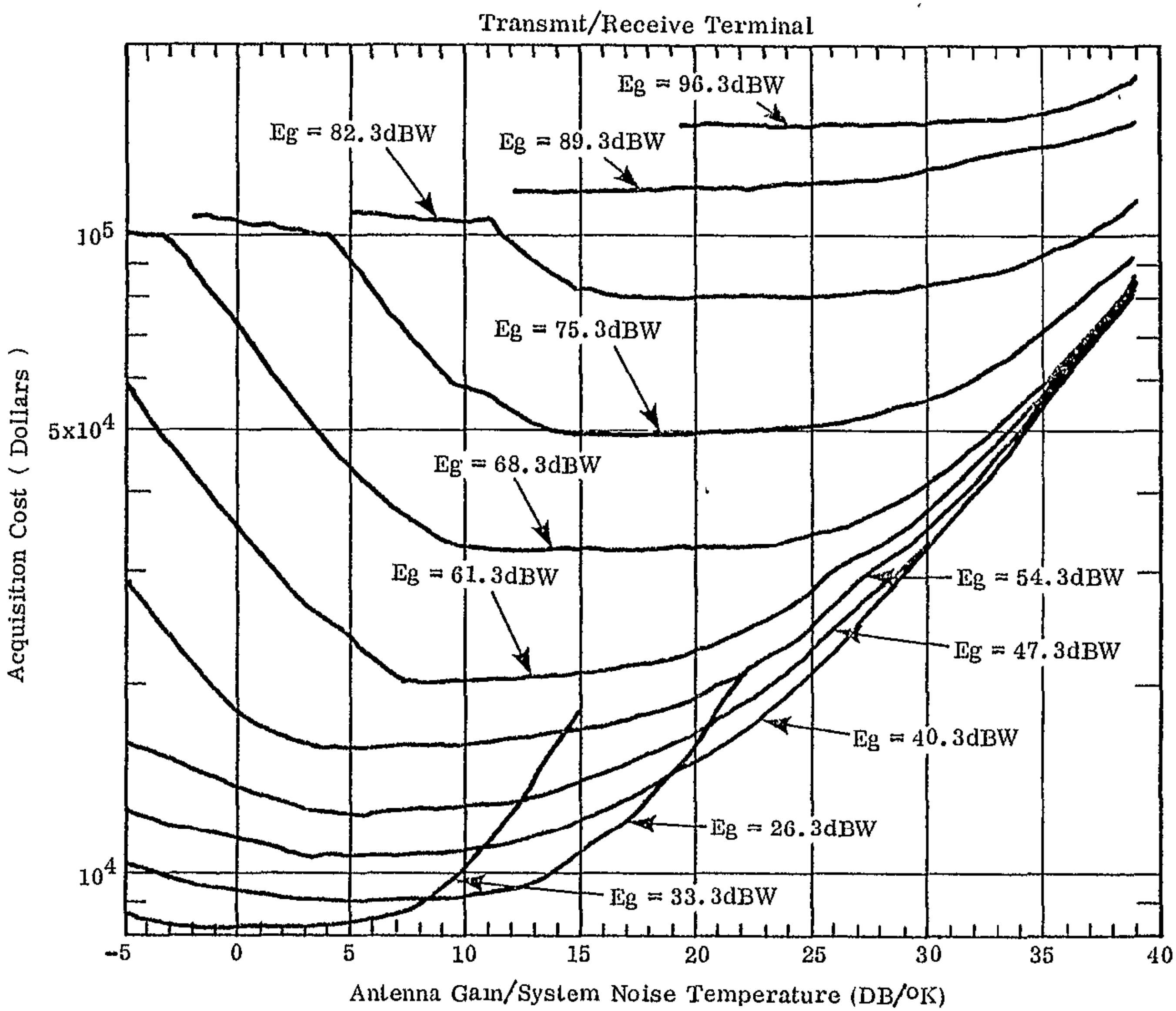

Figure 3-17. Ground Terminal Cost Vs. G/T Vs. EIRP (Eg)
(Ku-Band Redundant, 100 Units Procured)

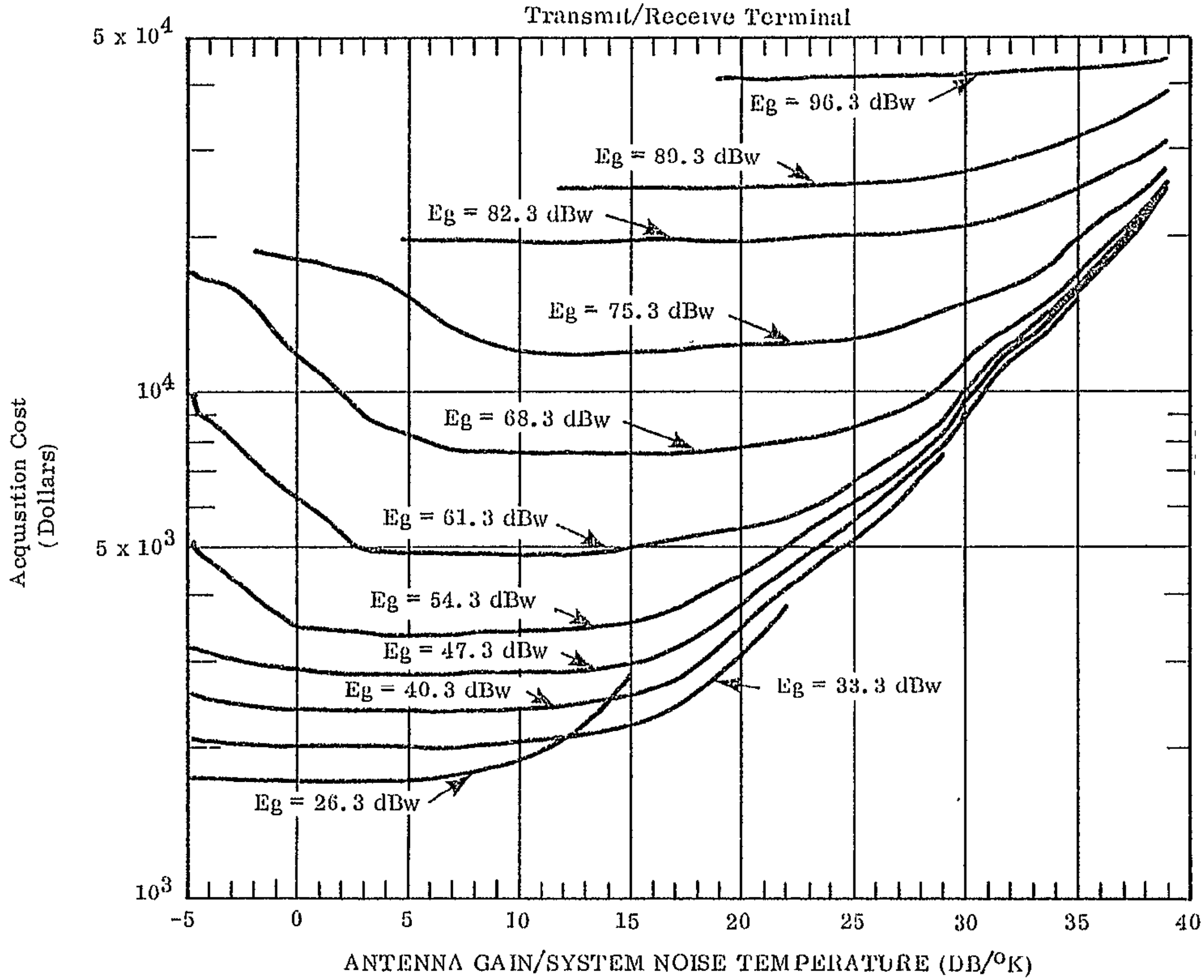

Figure 3-18. Ground Terminal Cost vs. G/T vs. EIRP (Eg)
(Ku-Band, Non-Redundant, 10^5 Units Procured)

Table 3-43 Optimum Ground Terminal Configuration vs. Performance (KuBand, Nonredundant Transmit/Receive, 10^2 Terminals)

G/T	E_G = 40.3 dBW			E_G = 68.3 dBW			E_G = 89.3 dBW		
(dB/°K)	PWR(dBW)	Gain (dB)	Temp(dB)*	PWR(dBW)	Gain(dB)	Temp(dB)*	PWR(dBW)	GAIN(dB)	Temp(dB)*
-5.0	1.00	38.00	43.00	29.00	38.00	43.00	-	-	-
-4.0	-0.00	39.00	43.00	28.00	39.00	43.00	-	-	-
-3.0	-1.00	40.00	43.00	27.00	40.00	43.00	-	-	-
-2.0	-2.00	41.00	43.00	26.00	41.00	43.00	-	-	-
-1.0	-3.00	42.00	43.00	25.00	42.00	43.00	-	-	-
0.0	-4.00	43.00	43.00	24.00	43.00	43.00	-	-	-
1.0	-5.00	44.00	43.00	23.00	44.00	43.00	-	-	-
2.0	-6.00	45.00	43.00	22.00	45.00	43.00	-	-	-
3.0	-6.00	45.00	42.00	21.00	46.00	43.00	-	-	-
4.0	-6.00	45.00	41.00	20.00	47.00	43.00	-	-	-
5.0	-6.00	45.00	40.00	19.00	48.00	43.00	-	-	-
6.0	-6.00	45.00	39.00	18.00	49.00	43.00	-	-	-
7.0	-6.00	45.00	38.00	17.00	50.00	43.00	-	-	-
8.0	-6.00	45.00	37.00	16.00	51.00	43.00	-	-	-
9.0	-7.00	46.00	37.00	15.00	52.00	43.00	-	-	-
10.0	-7.00	46.00	36.00	15.00	52.00	42.00	-	-	-
11.0	-7.00	46.00	35.00	15.00	52.00	41.00	34.00	54.00	43.00
12.0	-7.00	46.00	34.00	15.00	52.00	40.00	33.00	55.00	43.00
13.0	-7.00	46.00	33.00	15.00	52.00	39.00	33.00	55.00	42.00
14.0	-7.00	46.00	32.00	15.00	52.00	38.00	33.00	55.00	41.00
15.0	-7.00	46.00	31.00	15.00	52.00	37.00	33.00	55.00	40.00
16.0	-7.50	46.50	30.50	14.50	52.50	36.50	33.00	55.00	39.00
17.0	-7.50	46.50	29.50	14.50	52.50	35.50	33.00	55.00	38.00
18.0	-8.00	47.00	29.00	14.50	52.50	34.50	33.00	55.00	37.00
19.0	-10.00	49.00	30.00	14.50	52.50	33.50	33.00	55.00	36.00
20.0	-10.50	49.50	29.50	14.00	53.00	33.00	33.00	55.00	35.00
21.0	-11.00	50.00	29.00	14.00	53.00	32.00	33.00	55.00	34.00
22.0	-11.50	50.50	28.50	14.00	53.00	31.00	33.00	55.00	33.00
23.0	-12.50	51.50	28.50	14.00	53.00	30.00	33.00	55.00	32.00
24.0	-12.50	51.50	27.50	14.00	53.00	29.00	33.00	55.00	31.00
25.0	-13.00	52.00	27.00	14.00	53.00	28.00	33.00	55.00	30.00
26.0	-14.00	53.00	27.00	14.00	53.00	27.00	33.00	55.00	29.00
27.0	-14.00	53.00	26.00	14.00	53.00	26.00	33.00	55.00	28.00
28.0	-14.00	53.00	25.00	11.00	56.00	28.00	32.50	55.50	27.50
29.0	-16.00	55.00	26.00	10.50	56.50	27.50	32.00	56.00	27.00
30.0	-	-	-	10.50	56.50	26.50	31.50	56.50	26.50
31.0	-	-	-	10.50	56.50	25.50	31.50	56.50	25.50
32.0	-	-	-	10.00	57.00	25.00	31.00	57.00	25.00
33.0	-	-	-	9.50	57.50	24.50	30.50	57.50	24.50
34.0	-	-	-	9.00	58.00	24.00	30.00	58.00	24.00
35.0	-	-	-	8.50	58.50	23.50	29.50	58.50	23.50
36.0	-	-	-	8.00	59.00	23.00	29.00	59.00	23.00
37.0	-	-	-	7.00	60.00	23.00	28.00	60.00	23.00
38.0	-	-	-	6.50	60.50	22.50	26.00	62.00	24.00
39.0	-	-	-	6.00	61.00	22.00	26.00	62.00	23.00

*Receive system noise temperature represented in dB relative to 1°K

system noise temperatures from 65°K to 20,000°K, and transmitter power from 0.025 watts to 25,000 watts. This is done by making linear projections from cost data defined over the narrower bounds. However, because these were projections, it is believed that only terminal EIRP and G/T costs, corresponding to the narrow bounds on subsystem parameters, should be considered totally valid. The expanded bounds allow a selection/optimization process to occur even as the EIRP and G/T bounds are approached. Previously, there was only one antenna, receiver, and transmitter that could satisfy the bounding EIRP and G/T requirement. The projected subsystem bounds also allow smooth projections of EIRP and G/T in the few instances where they are needed by the system optimization algorithm (see Section 3.4).

Going from nonredundant receiver/transmitters to redundant receiver/transmitters increases ground terminal costs by a factor of slightly less than 2. The extent of variation can be seen by comparing Figures 3-16 and -17. It also causes lower performance receivers and transmitters to be paired with higher performance antennas. The extent of the change in pairings is illustrated in Table 3-44. As shown, the relative antenna gains deviate by from 0dB to as much as 3.5dB. At low values of G/T (e.g., 3dB/°K), there is no deviation. In this range, the transmitter cost dominates in both cases. This forces the antenna gain to the maximum consistent with the required G/T and a 43dB lower bound on allowable receiver performance. However, at higher G/Ts, the transmitter costs are driven down by increased antenna gains until an approximate balance is realized between antenna, transmitter and receiver costs. It is in this range that bigger antennas are matched with lower performance receivers and transmitters. As a rule of thumb, it appears that the antenna diameters increase by a factor of about 1.3 at the higher values of G/T (e.g., G/T $\geq$ 15dB/°K).

Increasing the yearly production volumes decreases ground terminal costs as displayed by Figures 3-16 and -18. The average rate of reduction is 25% to 30% per decade increase in yearly production. It does not vary significantly from non-redundant to redundant terminals but does tend to be slightly higher for the latter. The major price break occurs in going from 1000 to 10,000 units. With increased production, smaller antennas tend to be matched with higher performance transmitters and receivers. This is illustrated by Table 3-45. It is a result of a higher rate of cost reduction for transmitter/receiver technology as the production volumes increase.

B. OPTIMIZATION ALGORITHM

The optimization consists of selecting the minimum output of the ground terminal cost equation while selecting antennas, transmitters and receivers that satisfy terminal EIRP and G/T performance requirements. A large data base of antenna diameter versus cost, transmitter power versus cost, and receive system temperature versus cost serves as the means of obtaining corresponding cost/performance values for entry into the terminal optimization equations. The data base includes subsystem curves for production quantities of 10, 10^2, 10^3, 10^4 and 10^5 per year per manufacturer. The case of redundant transmitter/receivers is synthesized by doubling the cost of these items in the cost equation. The magnitude of the search makes a computerized approach necessary.

Table 3-44. Variation in Ground Terminal Configuration with Redundancy (Ku-Band, Eg = 68.3dBW, 10^2 Terminals)

G/T ($dB/^oK$)	Nonredundant Xmit/Receive			Redundant Xmit/Receive		
	PWR(dBW)	Gain (dB)	Temp(dB)*	PWR(dBW)	Gain (dB)	Temp(dB)*
-5.0	29.00	38.00	43.00	29.00	38.00	43.00
-4.0	28.00	39.00	43.00	28.00	39.00	43.00
-3.0	27.00	40.00	43.00	27.00	40.00	43.00
-2.0	26.00	41.00	43.00	26.00	41.00	43.00
-1.0	25.00	42.00	43.00	25.00	42.00	43.00
0.0	24.00	43.00	43.00	24.00	43.00	43.00
1.0	23.00	44.00	43.00	23.00	44.00	43.00
2.0	22.00	45.00	43.00	22.00	45.00	43.00
3.0	21.00	46.00	43.00	21.00	46.00	43.00
4.0	20.00	47.00	43.00	20.00	47.00	43.00
5.0	19.00	48.00	43.00	19.00	48.00	43.00
6.0	18.00	49.00	43.00	18.00	49.00	43.00
7.0	17.00	50.00	43.00	17.00	50.00	43.00
8.0	16.00	51.00	43.00	16.00	51.00	43.00
9.0	15.00	52.00	43.00	15.00	52.00	43.00
10.0	15.00	52.00	42.00	14.00	53.00	43.00
11.0	15.00	52.00	41.00	14.00	53.00	42.00
12.0	15.00	52.00	40.00	14.00	53.00	41.00
13.0	15.00	52.00	39.00	14.00	53.00	40.00
14.0	15.00	52.00	38.00	14.00	53.00	39.00
15.0	15.00	52.00	37.00	14.00	53.00	38.00
16.0	14.50	52.50	36.50	14.00	53.00	37.00
17.0	14.50	52.50	35.50	14.00	53.00	36.00
18.0	14.50	52.50	34.50	14.00	53.00	35.00
19.0	14.50	52.50	33.50	11.00	56.00	37.00
20.0	14.00	53.00	33.00	10.50	56.50	36.50
21.0	14.00	53.00	32.00	10.50	56.50	35.50
22.0	14.00	53.00	31.00	10.50	56.50	34.50
23.0	14.00	53.00	30.00	10.50	56.50	33.50
24.0	14.00	53.00	29.00	10.50	56.50	32.50
25.0	14.00	53.00	28.00	10.50	56.50	31.50
26.0	14.00	53.00	27.00	10.50	56.50	30.50
27.0	14.00	53.00	26.00	10.50	56.50	29.50
28.0	11.00	56.00	28.00	10.00	57.00	29.00
29.0	10.50	56.50	27.50	10.00	57.00	28.00
30.0	10.50	56.50	26.50	10.00	57.00	27.00
31.0	10.50	56.50	25.50	9.50	57.50	26.50
32.0	10.00	57.00	25.00	9.00	58.00	26.00
33.0	9.50	57.50	24.50	8.50	58.50	25.50
34.0	9.00	58.00	24.00	8.00	59.00	25.00
35.0	8.50	58.50	23.50	7.00	60.00	25.00
36.0	8.00	59.00	23.00	6.50	60.50	24.50
37.0	7.00	60.00	23.00	6.00	61.00	24.00
38.0	6.50	60.50	22.50	5.50	61.50	23.50
39.0	6.00	61.00	22.00	4.50	62.50	23.50

*Receive system temperature represented in dB relative to 1^oK

Table 3-45. Variation in Ground Terminal Configuration with Increased Production (Ku-Band, Nonredundant Transmit/Receive, Eg = 68.3 dBW)

G/T ($dB/^{o}K$)	10^2 Terminals			10^5 Terminals		
	PWR(dBW)	Gain (dB)	Temp(dB)*	PWR(dBW)	Gain (dB)	Temp(dB)*
-5.0	29.00	38.00	43.00	29.00	38.00	43.00
-4.0	28.00	39.00	43.00	28.00	39.00	43.00
-3.0	27.00	40.00	43.00	27.00	40.00	43.00
-2.0	26.00	41.00	43.00	26.00	41.00	43.00
-1.0	25.00	42.00	43.00	25.00	42.00	43.00
0.0	24.00	43.00	43.00	24.00	43.00	43.00
1.0	23.00	44.00	43.00	23.00	44.00	43.00
2.0	22.00	45.00	43.00	22.00	45.00	43.00
3.0	21.00	46.00	43.00	21.00	46.00	43.00
4.0	20.00	47.00	43.00	20.00	47.00	43.00
5.0	19.00	48.00	43.00	19.00	48.00	43.00
6.0	18.00	49.00	43.00	18.00	49.00	43.00
7.0	17.00	50.00	43.00	17.00	50.00	43.00
8.0	16.00	51.00	43.00	16.00	51.00	43.00
9.0	15.00	52.00	43.00	16.00	51.00	42.00
10.0	15.00	52.00	42.00	16.00	51.00	41.00
11.0	15.00	52.00	41.00	16.00	51.00	40.00
12.0	15.00	52.00	40.00	16.00	51.00	39.00
13.0	15.00	52.00	39.00	16.00	51.00	38.00
14.0	15.00	52.00	38.00	16.00	51.00	37.00
15.0	15.00	52.00	37.00	16.00	51.00	36.00
16.0	14.50	52.50	36.50	16.00	51.00	35.00
17.0	14.50	52.50	35.50	16.00	51.00	34.00
18.0	14.50	52.50	34.50	16.00	51.00	33.00
19.0	14.50	52.50	33.50	15.50	51.50	32.50
20.0	14.00	53.00	33.00	15.50	51.50	31.50
21.0	14.00	53.00	32.00	15.50	51.50	30.50
22.0	14.00	53.00	31.00	15.50	51.50	29.50
23.0	14.00	53.00	30.00	15.50	51.50	28.50
24.0	14.00	53.00	29.00	15.50	51.50	27.50
25.0	14.00	53.00	28.00	15.00	52.00	27.00
26.0	14.00	53.00	27.00	14.50	52.50	26.50
27.0	14.00	53.00	26.00	14.00	53.00	26.00
28.0	11.00	56.00	28.00	14.00	53.00	25.00
29.0	10.50	56.50	27.50	14.00	53.00	24.00
30.0	10.50	56.50	26.50	14.00	53.00	23.00
31.0	10.50	56.50	25.50	11.00	56.00	25.00
32.0	10.00	57.00	25.00	10.50	56.50	24.50
33.0	9.50	57.50	24.50	10.50	56.50	23.50
34.0	9.00	58.00	24.00	10.00	57.00	23.00
35.0	8.50	58.50	23.50	10.00	57.00	22.00
36.0	8.00	59.00	23.00	9.50	57.50	21.50
37.0	7.00	60.00	23.00	8.50	58.50	21.50
38.0	6.50	60.50	22.50	8.00	59.00	21.00
39.0	6.00	61.00	22.00	7.50	59.50	20.50

*Receive system temperature represented in dB relative to $1^{o}K$

The basic performance equations include an EIRP and a G/T equation. They are as follows:

$$G/T\ (\text{dB}) = G - T_S \qquad \text{and}$$

$$\text{EIRP}\ (\text{dBW}) = G + P_{GT} + 1.3$$

where:

- 1.3 is the factor by which the transmit antenna gain must be increased to account for operation at 14 GHz rather than 12 GHz.
- P_{GT} is the output power of the ground transmitter.
- All other parameters are as defined in Section 3.4.

NOTE: $G = 10 \log_{10} (\pi Df/C)^2_\eta$ where $\eta = 0.65$ for $D \geq 8$ ft and $\eta = 0.5$ for $D < (8\text{ ft})$

The nonredundant terminal cost, $C_T(\$)$, is determined as follows:

$$C_T(\$) = C_A + C_P + C_R$$

where:

- C_A is the per unit acquisition cost of the antenna.
- C_P is the per unit acquisition cost of the transmitter.
- C_R is the per unit acquisition cost of the receiver.

The redundant terminal cost, $C_T(\$)$, is determined as follows:

$$C_T(\$) = C_A + 2\ C_P + 2\ C_R$$

The process of generating the desired EIRP versus G/T versus cost curves begins by selecting the minimum EIRP and G/T values within the bounds indicated above (i.e., G/T = -5dB/°K and EIRP = 26.3dBW) and setting them into the performance equations. Then the minimum value of G within the expanded bounds of the antenna performance/cost curve is incremented into the performance equations. They are solved for T_S and P_{GT}. These values are compared with the expanded bounds of the receive system and transmitter performance/cost curves. If the values obtained are not on the curves, the incremental increase in G needed is computed and the appropriate G is set into the performance equations. With the bounding conditions satisfied, subsystem costs can be read off the data curves and set into the cost equation. The terminal cost for this configuration is calculated and the value stored. G is then incremented by 0.5dB, new values of T_S and P_{GT} are established, and a new terminal cost calculated and stored. This continues until the bound on one of the subsystem performance/cost curves is reached. When this

happens, all of the stored costs are reviewed. The minimum cost and corresponding subsystem configuration is selected and printed out. Then the G/T required is increased by 1 dB and the entire process above is repeated. This continues until the upper bound on G/T is reached. At this point, the G/T is reset to the minimum, the EIRP increased by 1 dB, and all of the steps above are repeated. This continues until the upper bound on EIRP is reached. At this point, the entire set of data for one size of procurement and one type of redundancy has been generated. Producing the other nine sets involves appropriately reselecting the subsystem performance/cost data and terminal cost equation and repeating the entire indicated process.

Examples of the performance/cost data inputs are provided in Section 3.6. Examples of the EIRP versus G/T versus cost outputs are given in Section 3.5.A above. The output cost data must be annualized before entry into the system optimization algorithm discussed in Section 3.4. Annualization is accomplished by multiplying the acquisition costs by a factor of 0.233. This includes a 0.07 factor to account for yearly maintenance costs and a 0.163 capital recovery factor. It is assumed that upon failure, a trained technician makes repairs. The capital recovery factor is based on making 10 equal payments, over a period of 10 years, to pay 10% of the undepreciated value each year and depreciate the investment to zero.

3.6 EARTH STATION CHARACTERISTICS SUMMARY

A secondary objective of the earth station evaluations completed, has been to identify critical technology which can significantly influence performance through 1985. Appendix 1, Volume 2, describes the earth station equipment and technology used in this study and presents the antenna gain vs cost, receiver noise temperature vs cost, HPA power vs cost, and interface equipment cost data for each service. A summary of these results is presented here. The reader is referred to the Appendix for further details.

Earth station equipment costs, in this study, are based on supplier surveys, catalogue prices and selected available quotations to ongoing equipment procurements. In developing this data, the earth station equipment is divided into two groups. In the first group, consisting of antennas, low noise receivers, high power amplifiers and related supporting equipment, specifications are prepared describing the salient performance and operating features required to provide the defined services. Occasionally this leads to dual specifications for different grades of performance. In addition, a questionnaire is prepared listing questions to be answered regarding the supplier's production methods, annual production and market growth, the industry market and sales growth, etc. Both specifications and questionnaire are mailed to prospective suppliers and followed up, in most cases, by company visits to review these documents, discuss technology and cost, and visit fabrication and test facilities. The suppliers respond with performance and cost data and judgment is used to compile the data to establish performance-cost trends.

In the second group, consisting of modulation, coding and multiplexing equipment and certain user equipments like video cameras, facsimile, data compressors

etc., the problem of identifying and costing is complex because of the equipment diversity. In some cases, for example TV cameras, facsimile, and MODEMS, quotes can be simply obtained from qualified suppliers. In most cases, however, such data was too difficult to obtain and costs were obtained by comparing the unit in question to units resembling them, in terms of components and devices used. Where circuitry is applicable, it is assumed that large scale integration is used for production quantities greater than 100,000. Of course LSI already is selectively used in many of the interface equipments. Finally, learning curves were either used directly for some items or used to check the cost trends developed from the supplier data.

Degree of subsystem redundancy, test equipment, alarm and monitoring, control, etc. were adopted as needed for each service. For TV broadcast direct-to-the user, a simple straightforward "single thread" earth station and modulation converter was configured, with no "frills." For multiplexed voice and data, full redundancy with the usual alarm, monitoring, control and test equipment was considered more appropriate. All earth station antenna costs include a 20% or $100 charge, whichever is larger, for installation.

No major technological breakthroughs are expected for earth station equipment through 1985. There is increasing use of solid-state HPAs for narrow band applications, of FETs for medium thermal-noise performance and a gradual improvement in performance or cost (in constant dollars) as the earth station industry grows and production increases. Two significant trends are worth noting. One is the expanding use of LSI, particularly MOS and I^2L in digital logic circuitry in particular. Much of currently available new earth station equipment uses LSI and the trend toward more extensive use is clear. However, much of the earth station equipment, particularly high cost items such as receivers, MODEMS, antennas, HPAs, etc. are not applicable to LSI. Where seemingly applicable, over the 1985 time frame, LSI is incorporated into equipments costed. The second trend worth noting is the substantial cost reductions achievable by large production buys. In fact, some of the terminal interface equipments are not cost-effective unless quantity buying and LSI can be used.

Results used, in both the transmit/receive and receive only final system tradeoffs, are summarized in this section. Figures 3-19, -20 and -21 show Ku-Band, S-Band and UHF receive system noise temperature, including the clear sky antenna noise contribution, versus cost with quantity purchased as a parameter. Also shown are the appropriate ranges of device performance. Figure 3-22 shows Ku-Band HPA power vs cost with quantity purchased as a parameter. Also shown are the appropriate ranges of device power performance. Ku-Band solid-state devices (FETs, or IMPATTS) appear practical at power levels up to 10 watts. TWTs and Klystrons are used above this power level. Figures 3-23, -24 and -25 show receive only antenna gain vs cost, with quantity purchased as a parameter, for Ku-Band, S-Band and UHF, respectively. Comparable transmit/receive antenna gain vs cost curves and complications of interface equipment cost are give in Appendix 1.

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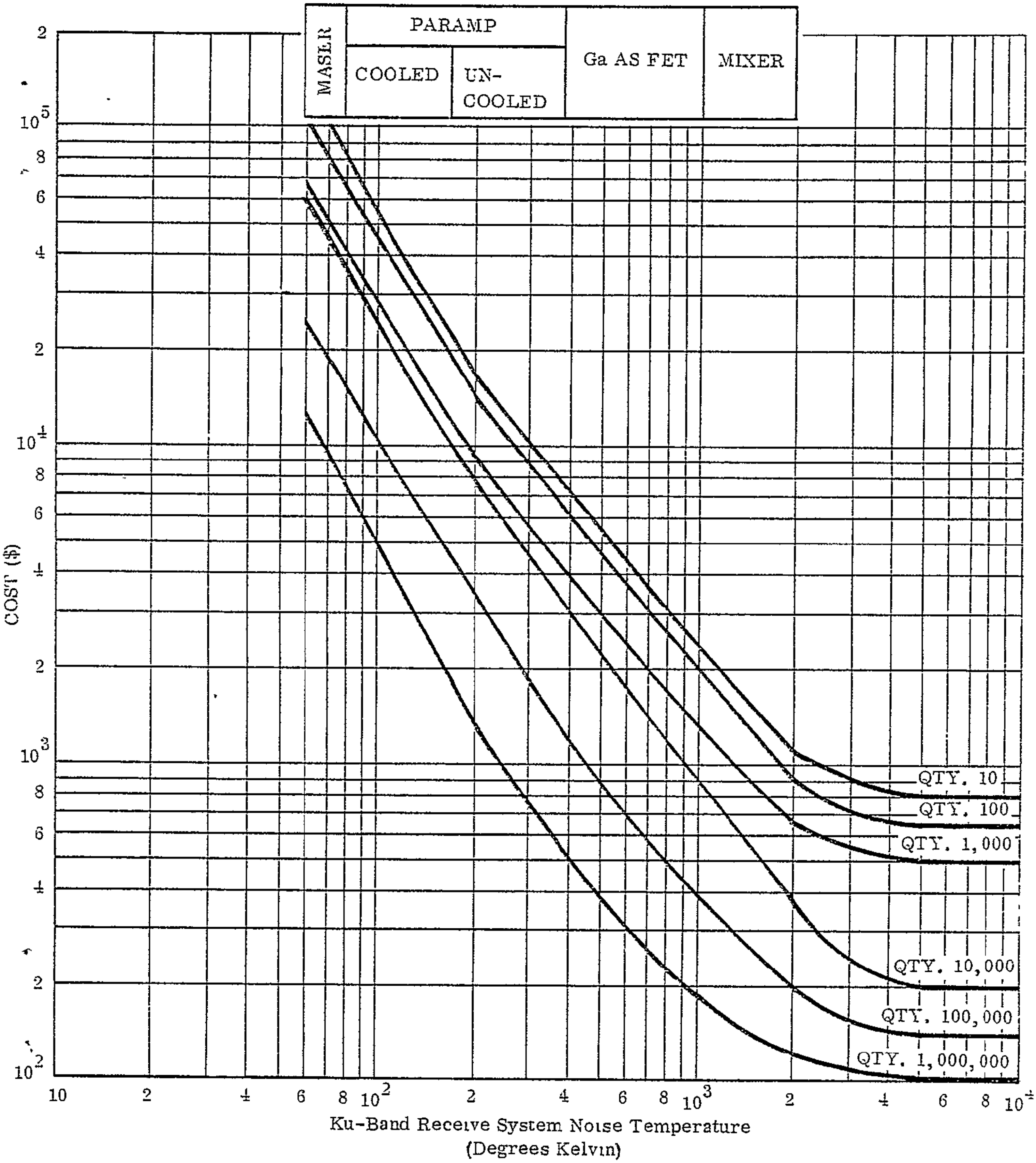
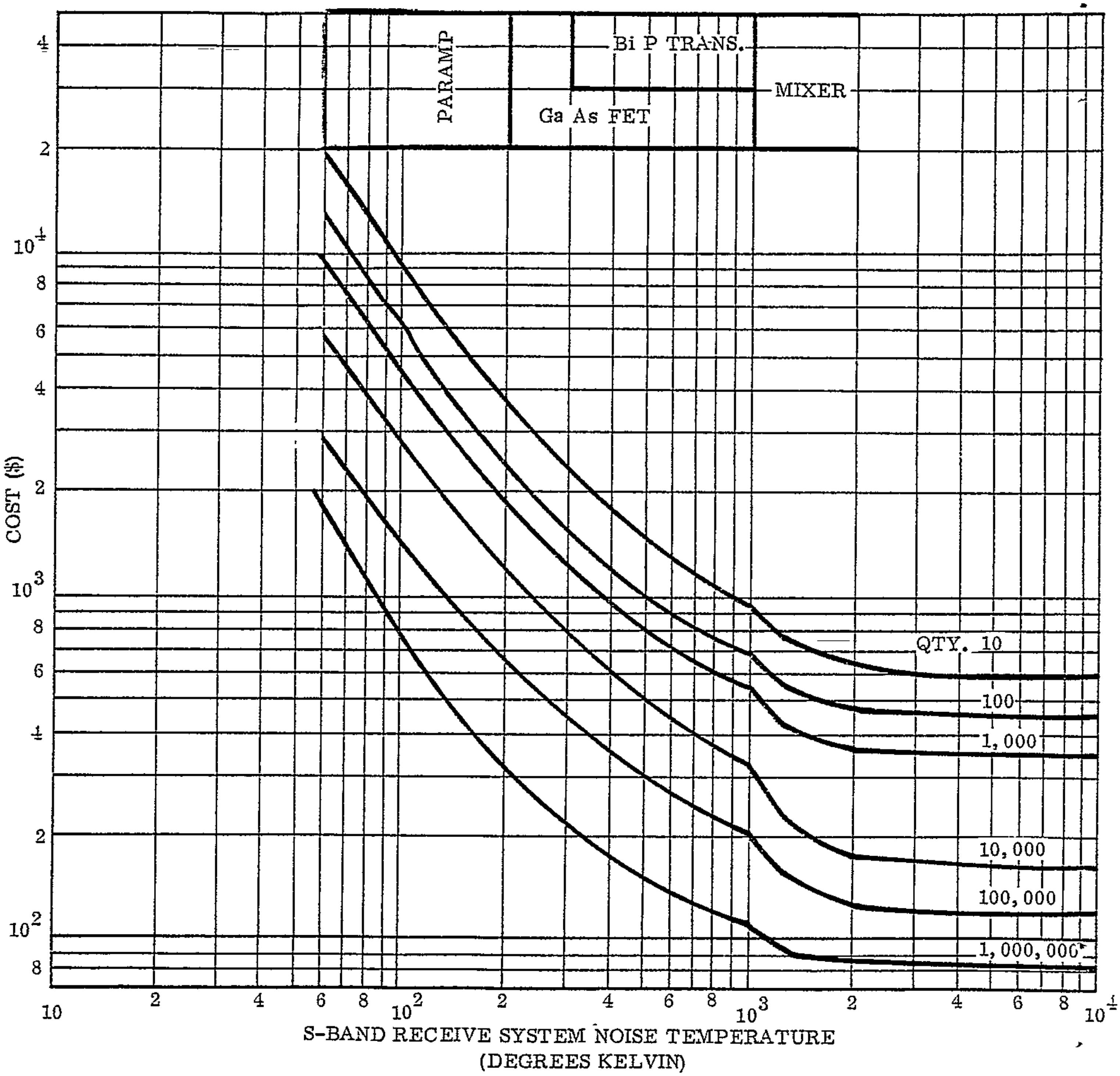


Note: Temperature includes 50°K antenna & feed system contribution.

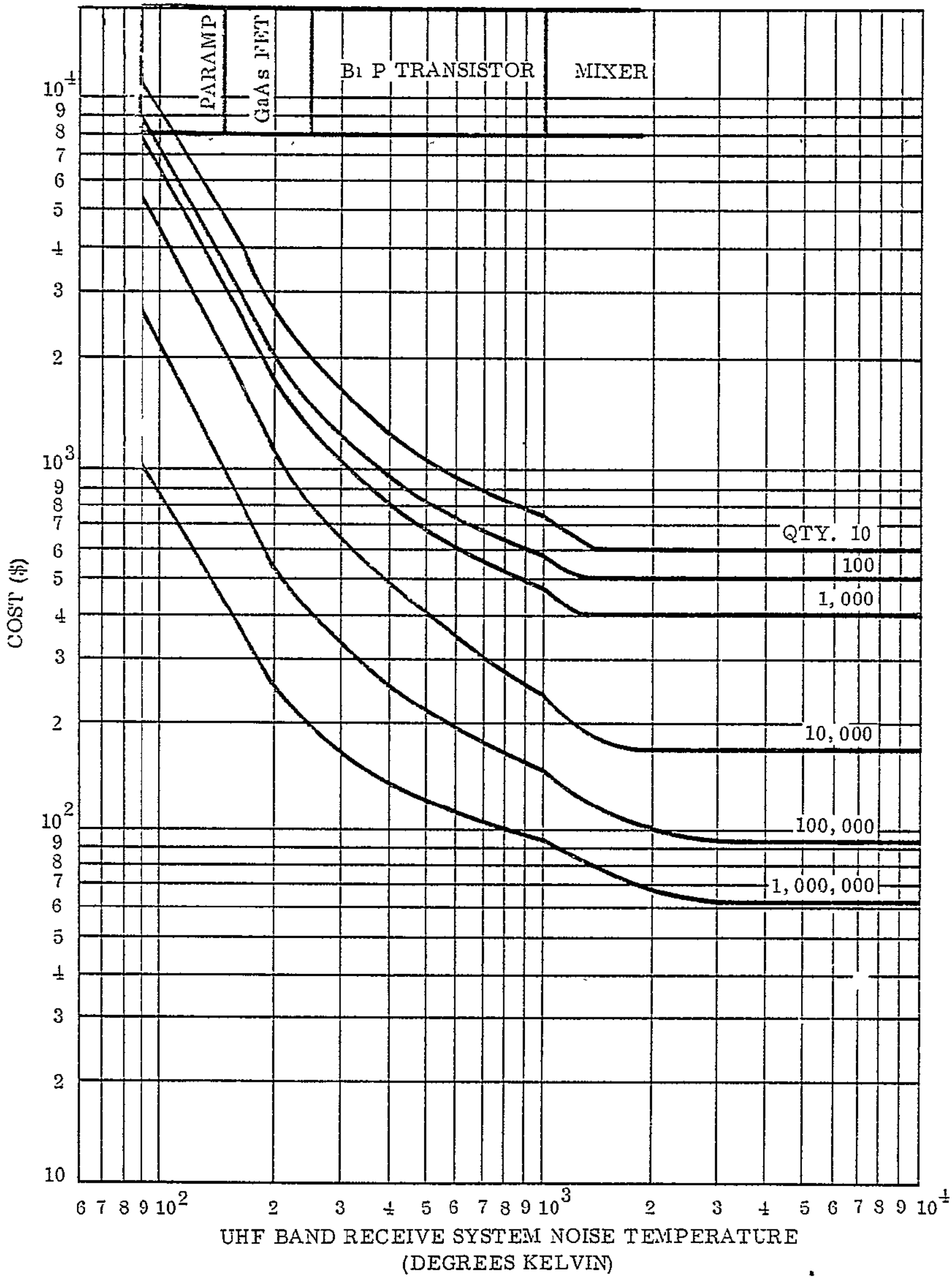
Figure 3-19. Ku-Band Receiver System Cost (1976) vs. Receive System Noise Temperature

C-3



Note: Temperature includes 40°K Antenna Feed System Contribution.

Figure 3-20. S-Band Receiver System Cost (1976) Vs. Receiver System Noise Temperature



Note: Temperature includes 40°K antenna & feed system contribution.

Figure 3-21. UHF Band Receiver System Cost (1976) vs. Receive System Noise Temperature

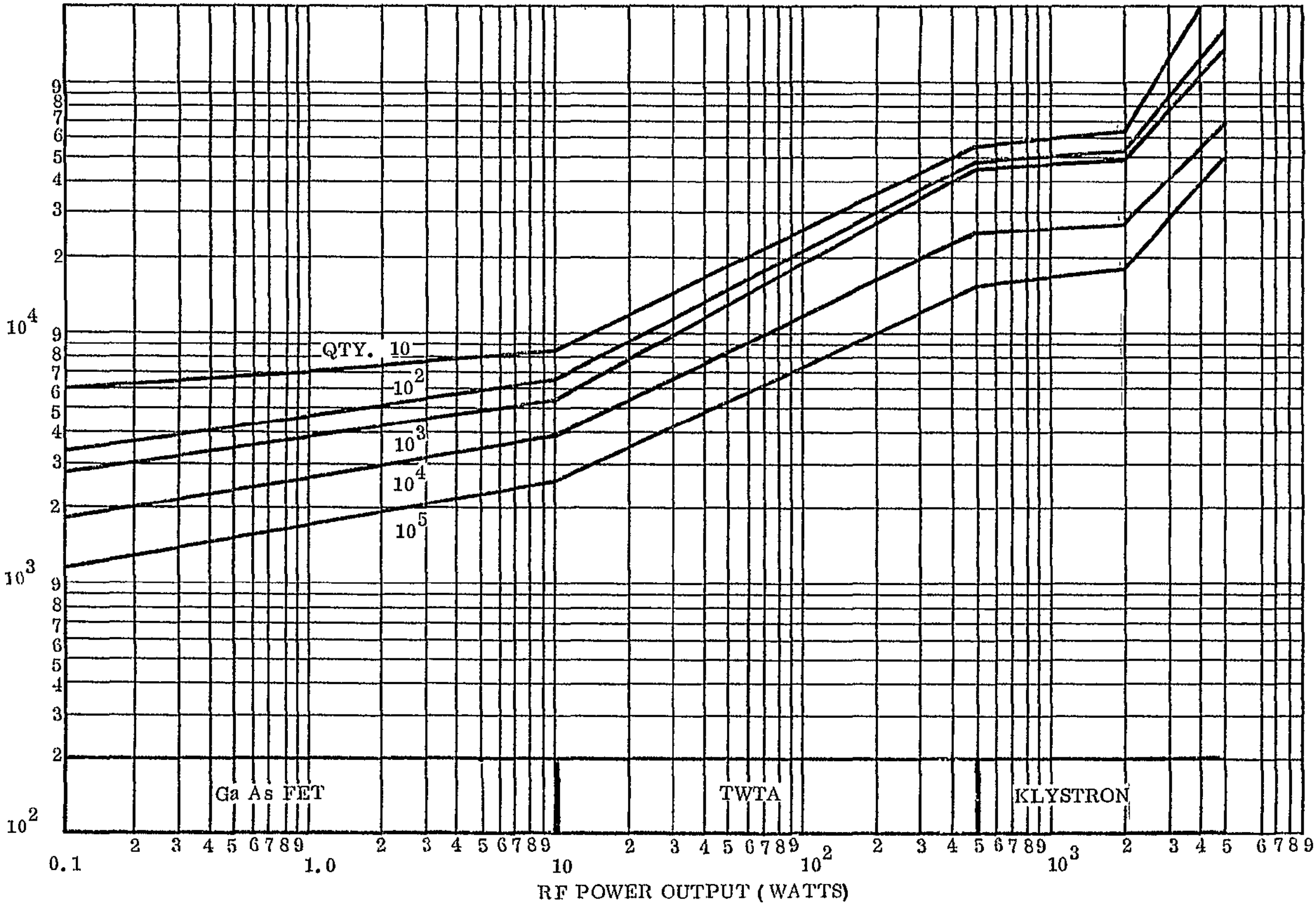


Figure 3-22. Ku-Band Power Amplifier System Cost (1976) vs. Output Power

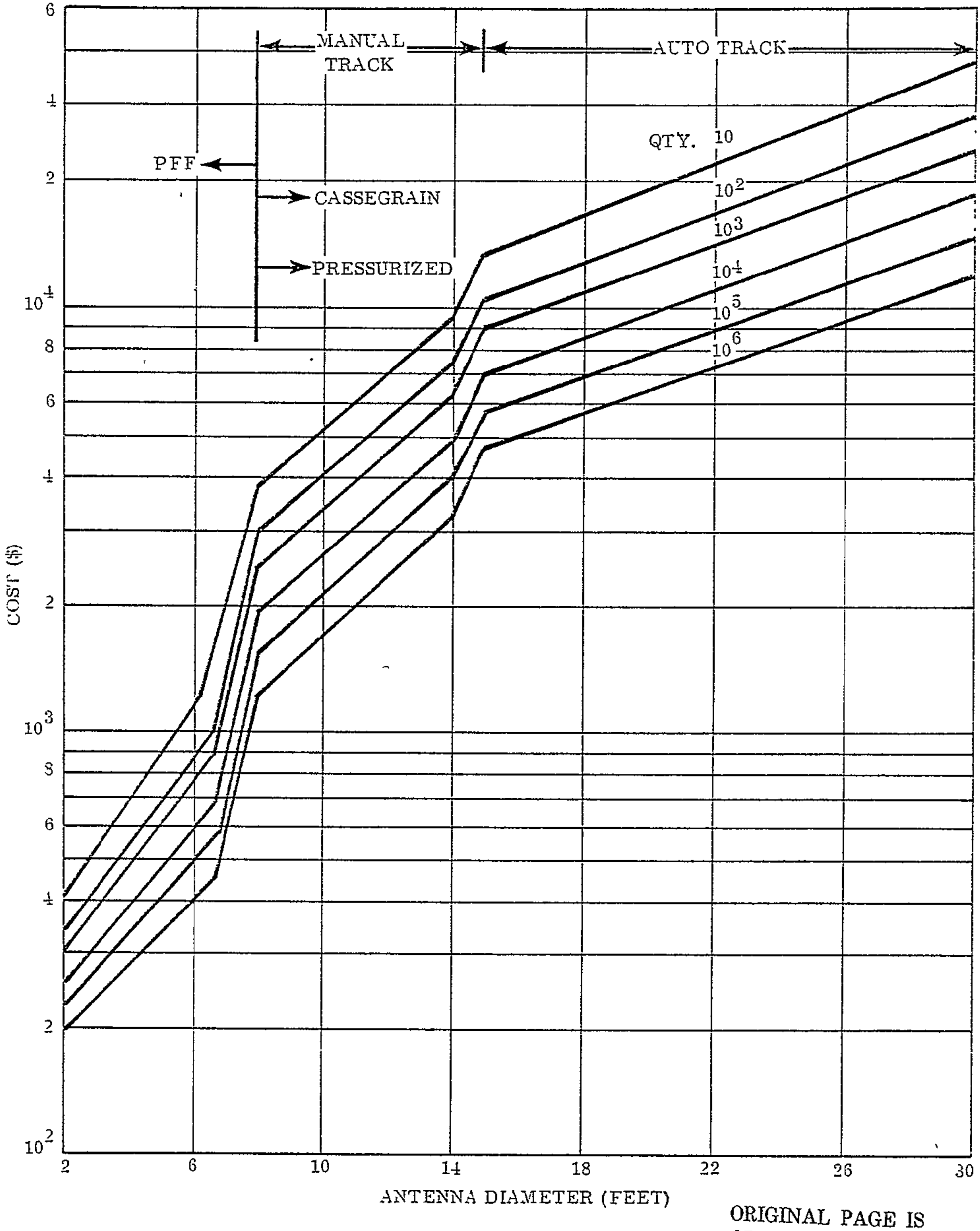


Figure 3-23. Ku-Band Antenna System Cost (1976) vs. System Diameter (Receive Only)

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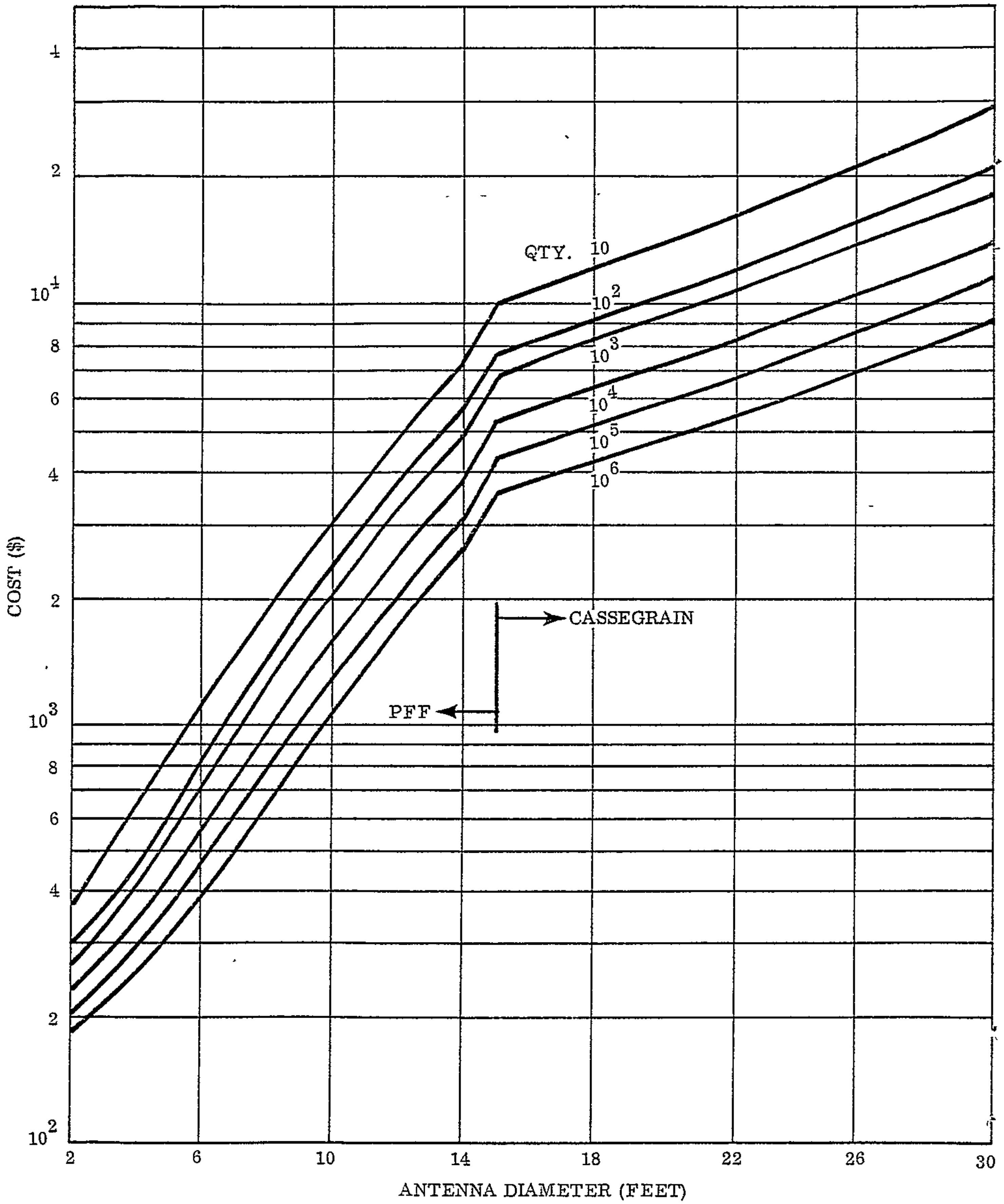


Figure 3-24. S-Band Antenna System Cost (1976) Vs. Antenna Diameter (Receive Only)

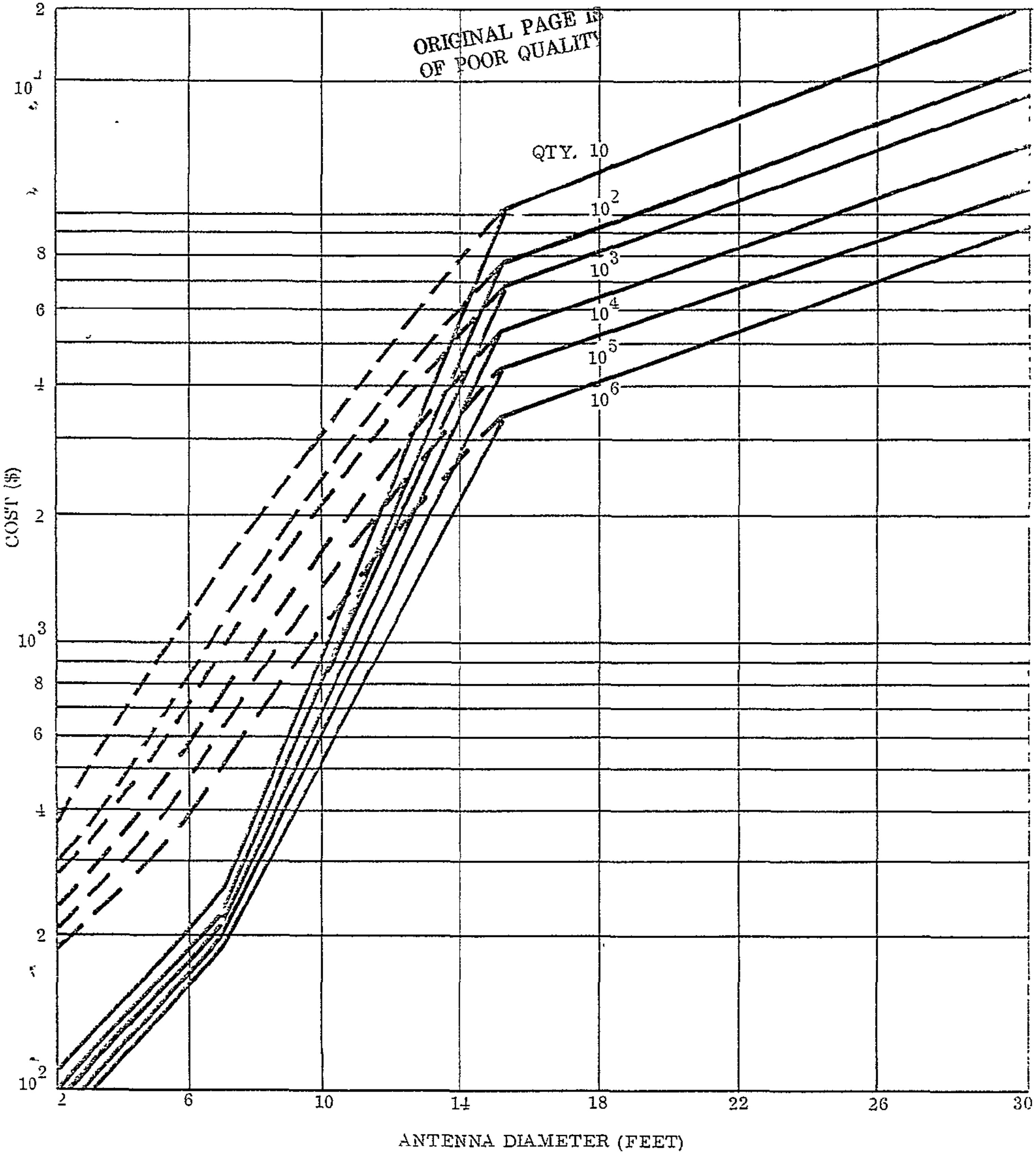


Figure 3-25. UHF Band Antenna System Cost (1976) vs. Antenna Diameter
(Receive Only - PFF)

3.7 SATELLITE CHARACTERISTICS

The satellite model used in this study, described completely in Appendix 2, Volume 2, enables an accurate representation of space system performance and cost. For the purpose of conducting the system tradeoff optimizations, the space segment EIRP per unit bandwidth is considered to be the dependent variable. This is accomplished, for each of the six launch vehicles, by varying the number of transponders per antenna beam per satellite. Thus, for the same launch vehicle the satellite communications transponders will change from a single high-powered transponder per beam to several or many lower powered transponders per beam. To accomplish this, the satellite communications payload diagrammed in Figure 3-26 is broken into its component parts and each part assigned a representative weight and, if applicable, power. These weights and powers are summed in terms of numbers of receivers, "M", per antenna beam, plus an allowance for redundancy, and in terms of numbers of transmitters per receiver, "N", as depicted in Figure 3-26. Also included in the communications payload are the antenna reflector and structural support and the prime power and energy storage systems energizing the communications payload. This is readily accomplished at Ku-Band, S-Band, and UHF. The general computational procedure is as follows:

1) Select one or four beams (M = 1 or M = 4)

2) Compute receiver weight and power

3) Let N = 1 (one transmitter per beam)

4) Compute transmitter weight (less weight and power of output amplifier)

5) Find weight and power of output amplifier, solar array and batteries (the latter are not included if the satellite is a broadcast satellite) that just consumes the satellite's available payload weight

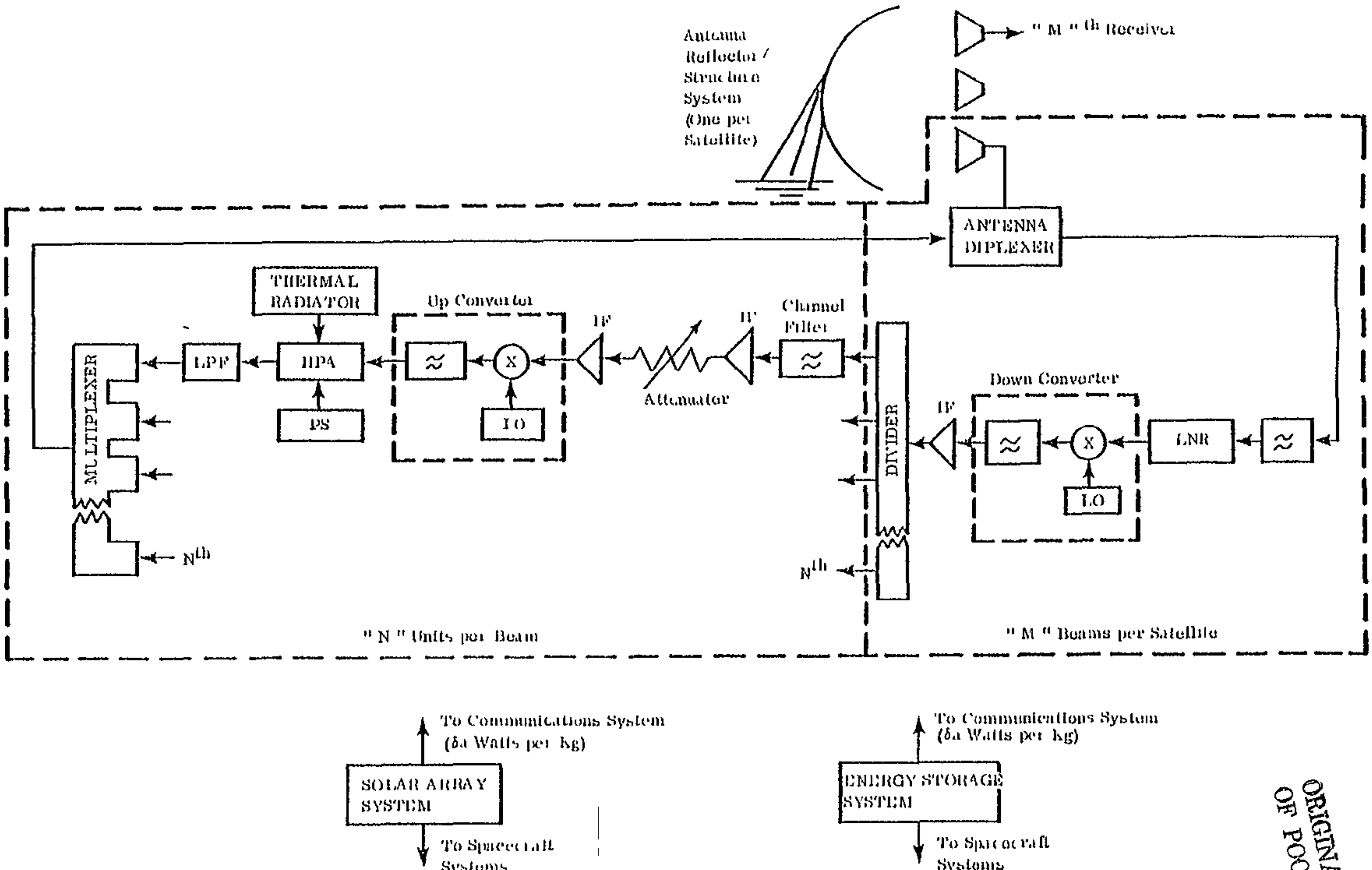
6) This identifies the satellite transmitter power, antenna gain and hence EIRP

7) Repeat the above for N = 2

8) Continue incrementing N until the transmitter power falls below 1 watt

The UHF land mobile satellite is somewhat different in that it has multiple beams with one transponder (plus redundancy) per beam, and more efficient solar arrays and energy storage.

In general, there is a non-linear relation between transmitter power and weight which is defined by available and projected transmitters in the three frequency bands (TWTs are assumed for Ku-Band and S-Band, and multiple silicon bipolar



Note: For Convenience, Receive and Transmit Beams are Coaxial
Use of Dual Polarization, If Needed is Treated as Additional Beams

Figure 3-26. Present Technology Broadcast Transponder Arrangement

transistors are assumed at UHF). This process results in a variation of transponders and hence transmitter power for each launch vehicle for each of the three frequency bands. Satellite communications payload is determined in Appendix 2, Volume 2, to be a fixed portion of the total beginning of life mass in synchronous orbit. This is an accurate representation for operational communications satellites using spin or wheel stabilization and monopropellant hydrazine for 7 years of north-south stationkeeping. The land mobile satellite's transmitter power versus weight relationship is somewhat different. This satellite may use a very large multiple beam antenna, special diplexing filters and linearized Class B amplifiers to favor operation with multiple carriers.

Launch vehicle costs are based on 1976 costs for the Delta 2914, Delta 3914 and Atlas Centaur. Shuttle capabilities are based on projections of SSUS (solid spinning upper stage) performance, essentially emulating Delta 3914 and Atlas Centaur payloads, and IUS (interim upper stage) performance, allowing a dedicated spacecraft launch on shuttle. Costs are based on 1976 NASA projections and are given in Table 3-46. Satellite costs for these launch vehicles are obtained by comparing the subject satellites to one or more operational satellites of the same mass (e.g., same launch vehicle) and exercising some judgment to arrive at an accurate and mutually consistent set of satellite costs.

Since annual, not acquisition, costs are needed for the tradeoffs, other costs including non-recurring and recurring capital costs and operating expenses must be considered. Major items included are acquisition costs for three satellites (one a ground spare), two launch vehicles, launch and on-orbit insurance, control center and antenna tracker, launch team costs, computer costs, operational engineers, operators and maintenance technicians. Capital costs are depreciated over seven years with a return on investment of 10%. Typical satellite carrier overhead is assumed to be 100%, G&A to be 25% and average profit to be 15%. This results in the annual space segment costs given in Table 3-47.

Annual space segment cost "A" is multiplied by a factor F to obtain the annual transponder charge where:

$$F = \frac{1}{f\,NM}$$

where: N = number of active* transponders
M = number of simultaneous antenna beams (M = 1 or M = 4)
f = satellite fill factor

Satellite fill factor = 0.65 for fixed service type satellites (e.g., satellites with many transponders). It takes into account the fact that the satellite is not fully loaded until the seventh year of operation. It is based on a traffic growth rate of 15% per annum.

*e.g., not standby transponders

Table 3-46. Launch Vehicle and Satellite Cost Data

Launch Vehicle Data	Sync Orbit Capability Kg	Total Cost per Launch, 1976 $M "A"	Reliability (6)
Delta 2914	349 (3)	14.2	.9
Delta 3914	454 (3)	15.4	.9
Atlas Centaur	998 (3)	24.9	.9
Shuttle/ SSUS (1)(four/ launch)	454	7.3 - 8.0 7.7 (4) (5)	.99
Shuttle/ SSUS (two/ launch)	998	14.4 - 15.8 15.1 (4) (5)	.99
Shuttle/ IUS (2) (one/ launch)	2268	24.8 - 27 25.9 (5)	.99

(1) SSUS - Spin Stabilized Upper Stage, e.g., perigee injection
(2) IUS - Interim Upper Stage - perigee/ apogee tandem stage, 3-axis stabilized - this implies NASA responsibility for transfer orbit, e.g., T&C not required
(3) Estimated from transfer orbit capability
(4) Converted from 1975 to 1976 dollars at rate of 7 percent per annum
(5) Includes cost of SSUS/ IUS
(6) Estimate

Table 3-47 Annual Space Segment Costs

	Launch Vehicles	Satellite Annual Cost ($M)	Annual Space Segment Costs 1976 - $M
Expendable	2914	13	19.4
	3914	16	21.7
	A/ C	23	32.7
Shuttle	3914	16	17.4
	A/ C	23	26.1
	Dedicated	36	40.2

Table 3- 48. Useful UHF Power for Land Mobile Service

Launch Vehicle	Ant. Dia.	MPT* KW	Space Segment Annual Cost
Dedicated Shuttle	(210')	5.2	$47.4M
Dedicated Shuttle	(120')	8.8	44.6
Dedicated Shuttle	(60')	11.7	42.4
Dedicated Shuttle	(30')	11.7	41.4
A/ C Shuttle	(120')	2.5	33.3
A/ C Shuttle	(60')	4.5	28.3
A/ C Shuttle	(30')	5.0	27.3

*Total useful instantaneous power including backoff but excluding activity factor

Figure 3-27 shows single beam Ku-Band transponder cost versus power curves for the six launch vehicles. Costs are an allocation of the annual cost for the entire space segment. The lower (flat) portion of the curves represent satellites having many low-powered transponders while the upper portion represents satellites with a limited number of high-powered transponders (e.g., a broadcast satellite). Moving vertically on this graph indicates the economy of scale in using larger satellites. That is provided they are reasonably filled. Figure 3-27 actually depicts a broadcast satellite characteristic, because no eclipse capability is provided. However, the fixed service satellite characteristic, in which the eclipse capability is provided, is almost the same and is given in Appendix 2.

Figure 3-28 shows a similar Ku-Band satellite characteristic for a four-beam (time zone case). The extra weight for antennas, feeds and receivers flattens the lower portions of the curves. This, and the fact that a minimum of four transmitters are provided, terminates the upper end of the curves at lower transponder powers. Note that the termination is also at a slightly lower composite satellite power level.

Figure 3-29 shows similar characteristics for a single beam S-Band broadcast satellite. Figure 3-30 shows similar characteristics for a four-beam S-Band broadcast satellite. Once again the additional "flatness" and lower composite power, because of the added antenna and receiver weight, are displayed.

Figure 3-31 shows similar characteristics for a single beam UHF broadcast satellite. Only the three larger launch vehicles are considered for broadcasting at UHF because of the large antenna needed. Figure 3-32 shows a similar characteristic for a four-beam UHF broadcast satellite. In this case, the antenna is even larger.

These characteristics describe space segment performance and cost for the broadcast and fixed services. The reader is urged to read Appendix 2 for more details. The land mobile space segment, providing UHF communications to land mobile vehicles and Ku-Band communications to the fixed terminals, uses a more efficient power system and linearized Class B amplifiers. It is not treated parametrically by the computer. The final characteristics achieved are given in Table 3-48. In the table, MP_T is the total useful transmitter power available and the space segment annual cost has been modified slightly to account for the added cost of the large antennas.

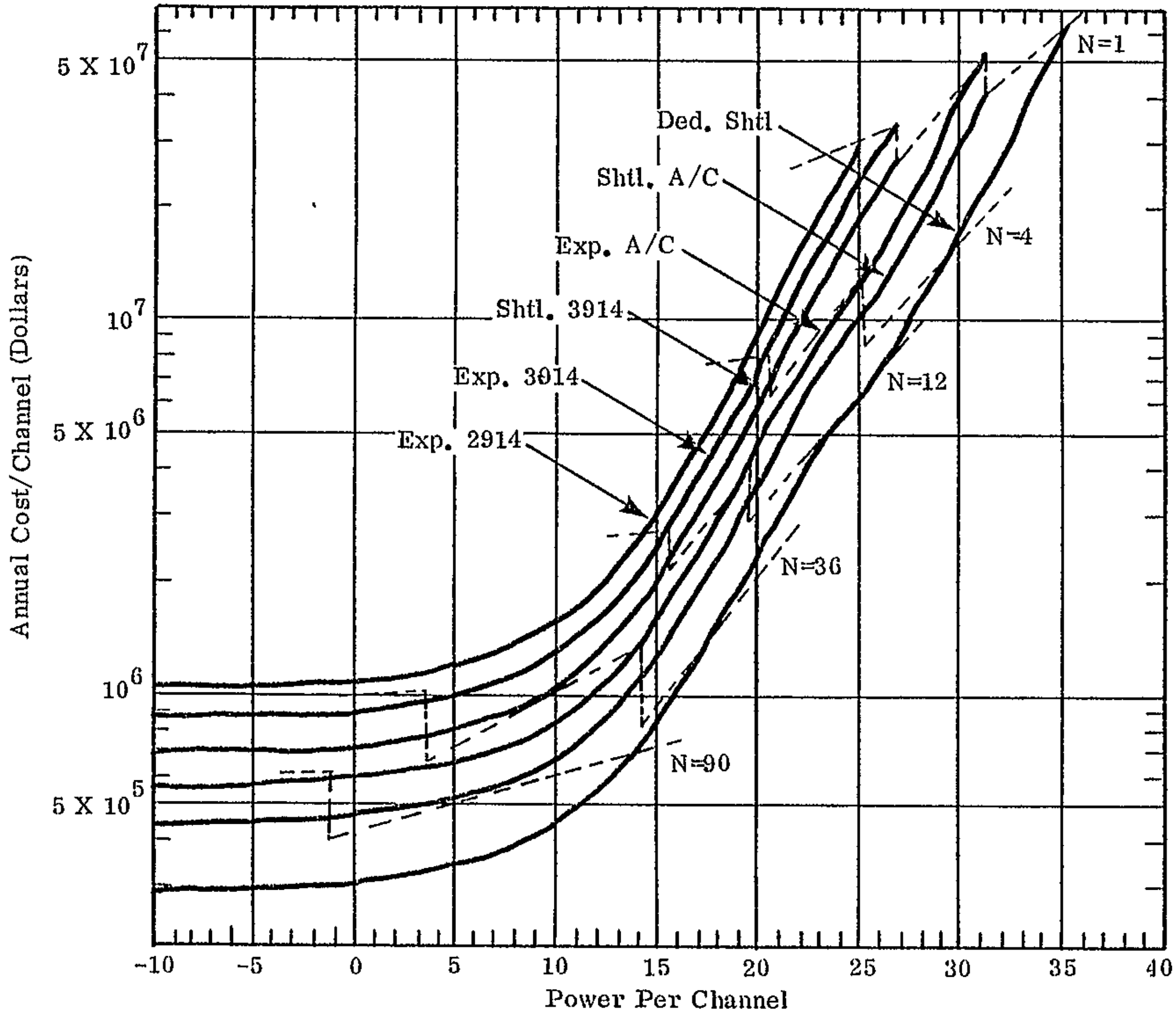


Figure 3-27. Satellite Channel Cost Vs. Power (Ku-Band, 1 Beam, Broadcast)

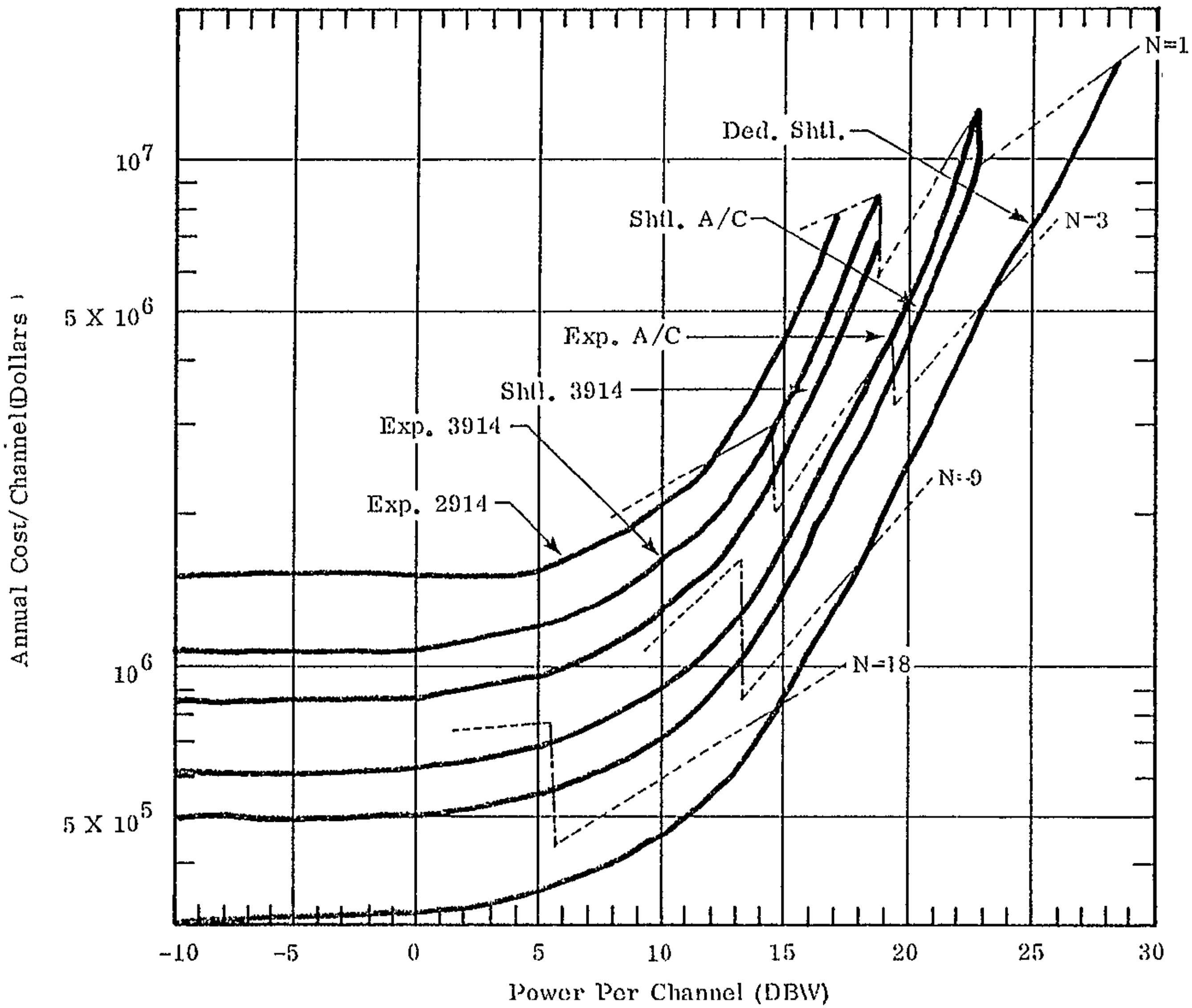


Figure 3-28. Satellite Channel Vs. Power
(Ku-Band, 4 Beams, Broadcast)

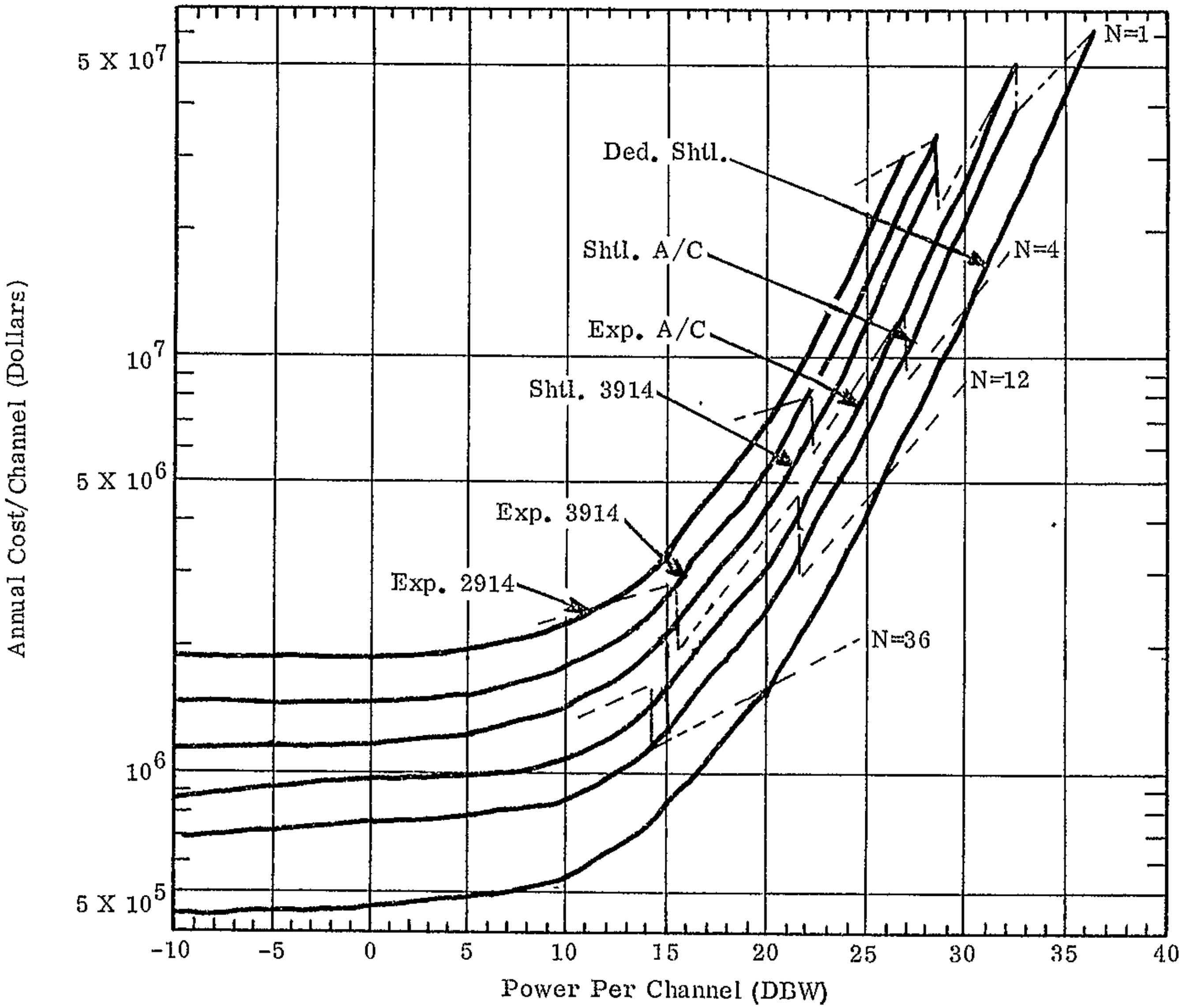


Figure 3-29. Satellite Channel Cost Vs. Power (S-Band, 1 Beam, Broadcast)

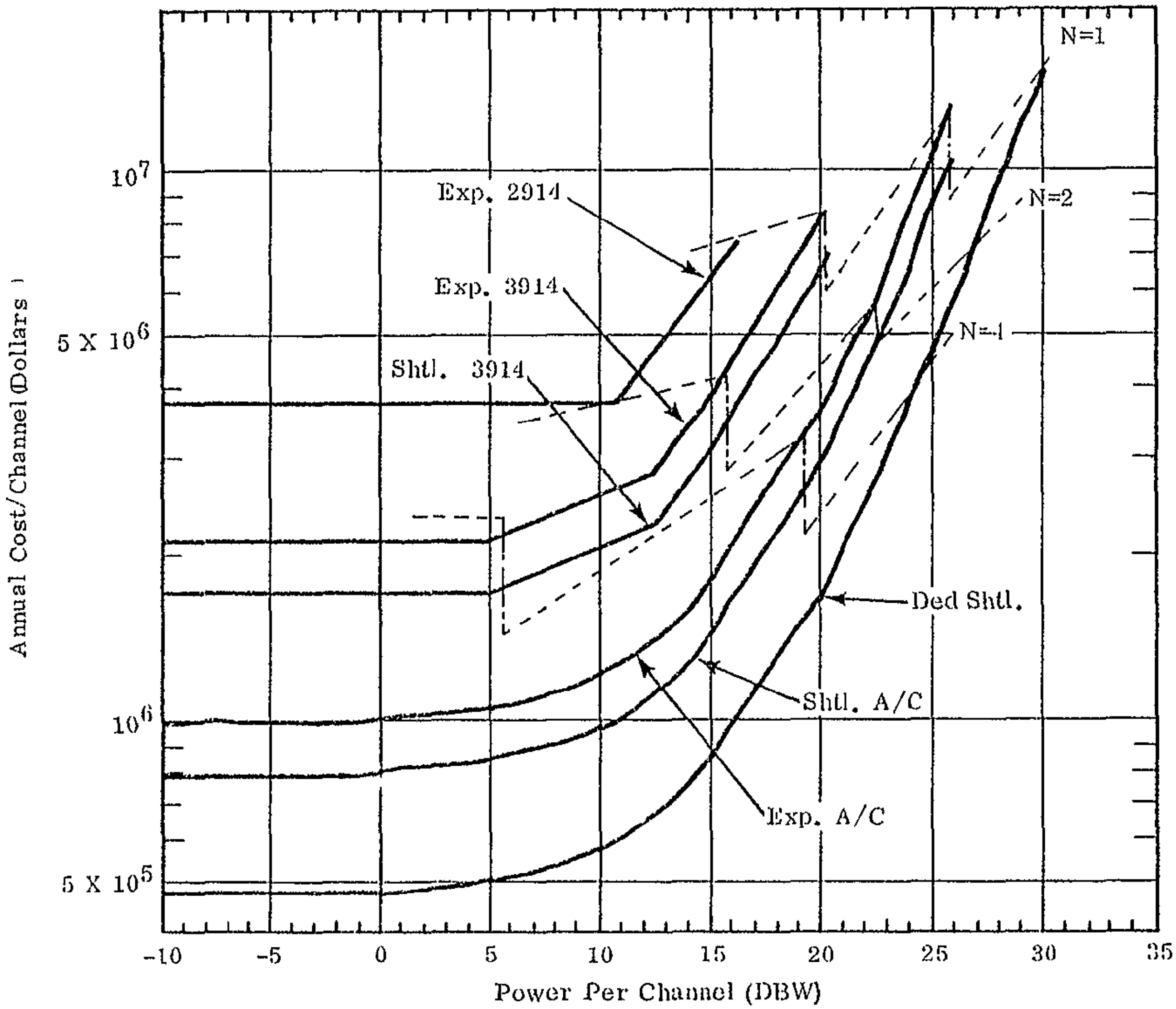


Figure 3-30. Satellite Channel Cost Vs. Power
(S-Band, 4 Beams, Broadcast)

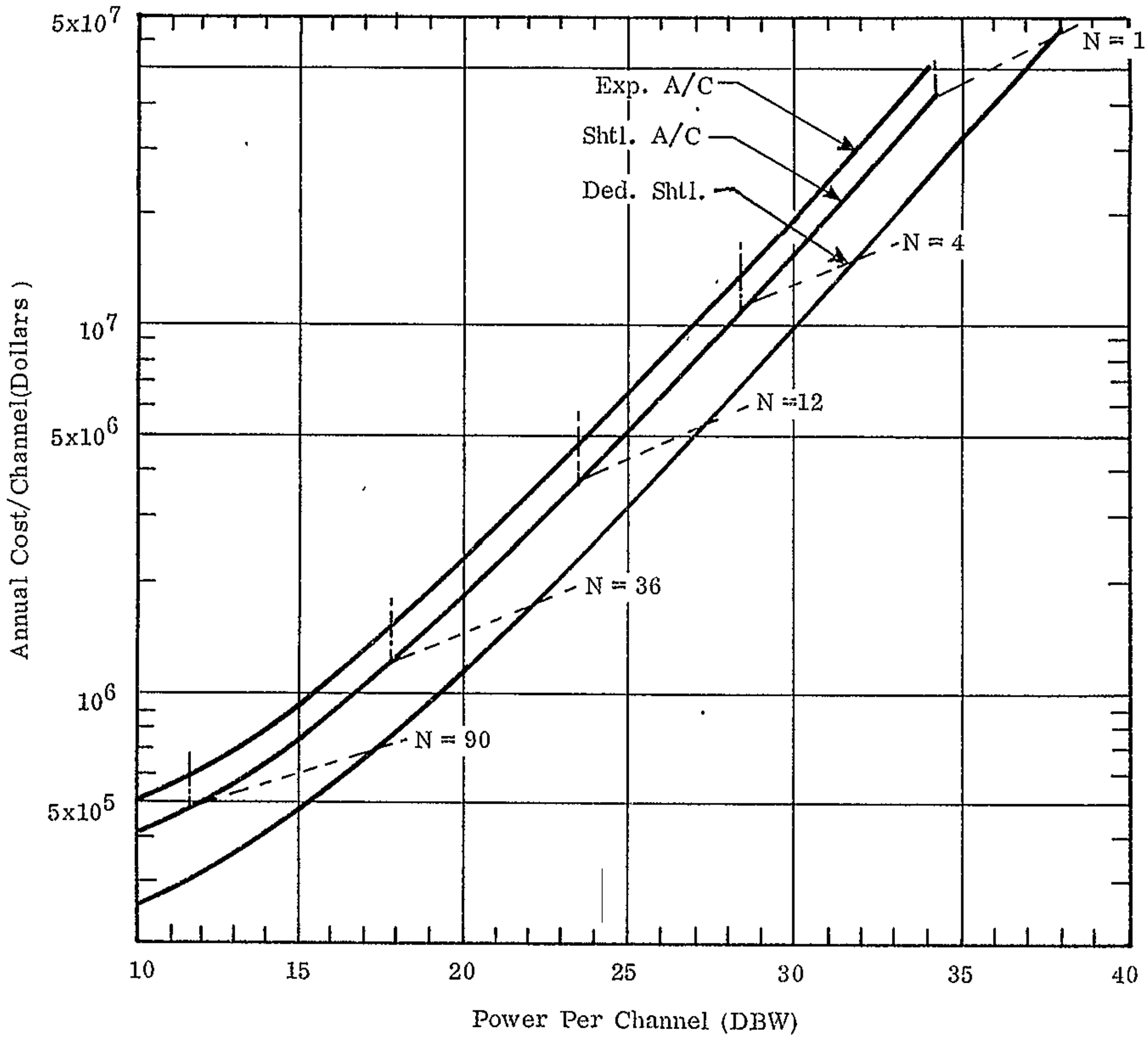


Figure 3-31 . Satellite Channel Cost Vs. Power (UHF, 1 Beam, Broadcast)

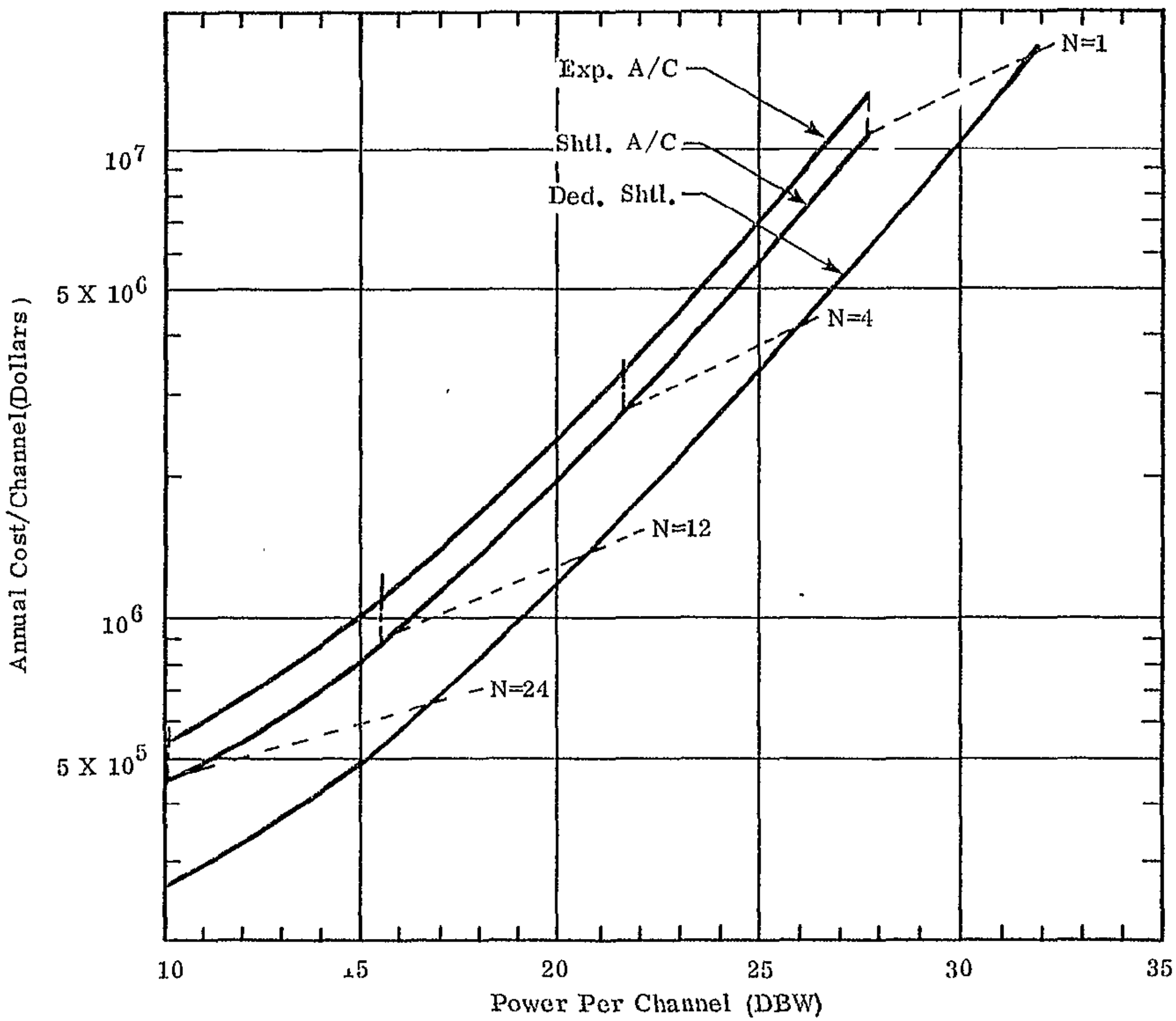


Figure 3-32. Satellite Channel Cost Vs. Power (UHF, 4 Beam, Broadcast)

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SECTION 4

TRADE-OFFS, BROADCAST SERVICES

4.1 INTRODUCTION

A. OVERVIEW OF RESULTS

Five special broadcast services are subjected to trade-off evaluations as a function of a wide variety of system options, to develop optimized satellite/ground terminal configurations and user annual costs at Ku-band and S-Band. UHF operation also is evaluated in two of the services. The services and representative examples of trade-off results are depicted in Table 4-1. The TV Direct to the User and FM Voice/Music Direct to the User services are applicable to UHF operation. The services are not presently supplied on a major scale by communications carriers, and are somewhat unique in that small earth terminal antennas and high powered satellite are necessary for a cost effective service.

The "TV for Retransmission" service is configured for U.S.-wide TV signal distribution for the broadcasting networks (e.g. ABC, CBS, etc.) and CATV head end terminals, and similar applications. Accordingly, a high quality signal is assumed. The "TV Direct to the User" service provides educational and instructional TV broadcasts direct to the home, factory or school. Consequently, a lower quality signal is assumed. The "FM Voice/Music for Retransmission" service supplies U.S.-wide radio signal distribution for the broadcasting networks (e.g. ABC, CBS, etc.). A 15 KHz high quality baseband is assumed. The "Compressed Bandwidth TV" service is configured as an alternate means of supplying educational and instructional TV, based upon reducing transmission requirements to save costs. The "FM Voice/Music Direct to the User" service makes educational, instructional, and hazard warning programming available direct to the home, factory or school. An 8 KHz lower quality signal compatible with the user's needs is assumed.

The basic system configurations, displayed in Table 4-1, are chosen to be representative of the small antenna networks that might reasonably be implemented before 1985. The satellite and earth station configurations and costs for a wider range of networks and launch vehicles are given in Section 4.3. It is generally expected that the networks will be larger as the service bandwidth decreases for direct broadcasts to the user. The network service ranges from 100 terminals for high quality TV for redistribution, to 10^6 terminals, for radio service directly to the user.

Table 4-1. Summary Optimized Systems Annual Cost and Configurations

	System Conf.				Gn'd Term. Conf.		Sat. Config.			Average System Cost/Term				
										Total Per		% Due to		
Service	Total Term.	No. Term/ Sat. Sig.	Launch Vehicle	Freq. Band	Ant. Dia. (M)	Rec'v'r Temp. (°K)	No. Beams	No. Sigs/ Channel	Sat. Pwr. per Chan. (W)	Year	Month	Sat.	Term	Fixed
TV for Retransmission	10^2	25	Shuttle	Ku	9.9	265	4	1	5	$35K	$2.9K	68	27	5
			A/C	S	4.7	160			4	$39K	$3.3K	86	10	4
TV Direct To User	10^4	2,500	Shuttle	Ku	3.7	640	4	1	50	$2.1K	$175	40	58	2
			A/C	S	2.1	280			25	$1.1K	$ 95	45	50	5
				UHF	2.4	360			28	$645	$ 54	47	44	9
FM Voice/ Music for Retransmission	10^4	625	Shuttle	Ku	2.3	1200	4	32	110	$1.4K	$115	18	46	36
			A/C	S	1.8	1600		64	125	$930	$ 78	9	36	55
Compressed Bandwidth TV	10^4	625	Shuttle	Ku	2.3	580	4	2	17	$7.1K	$590	15	4	81
			A/C	S	1.8	510		3	20	$6.7K	$560	9	6	84
FM Voice/ Music Direct To The User	10^6	250,000	Shuttle	Ku	1.5	3100	4	20	180	$180	$ 15	1	71	28
			A/C	S	0.33	1200			350	$105	$ 9	2	50	48
				UHF	0.45	2500			560	$ 85	$ 7	2	39	59

Typical launch vehicles are the Atlas Centaur and Dedicated Shuttle. Satellites of this size result in an economy of scale that reduces the annual cost per user. At Ku-band, the individual services require from 4.5% to 20% of the available Atlas Centaur satellite payload and the composite payload of the five services is about 55%. If a Dedicated Shuttle is employed, the payload is approximately half as large (ie, 30%). If S-band or UHF is used, both the Atlas Centaur and Dedicated Shuttle payloads are reduced by about half. This does not consider the application of flux density limits to the S-band service. When this is considered, the S-band satellite requirements become even smaller. It is interesting to note that if the "Mobile Radio" service was set aside, all of the requirements listed in Table 3-1 and Table 4-1 can be met with a combined Ku-band/S-band Atlas Centaur sized satellite payload. If a Dedicated Shuttle is employed, a considerable UHF mobile radio capability can be added.

As explained in Section 3.1.A, the average number of terminals per carrier "slot" in the satellite is a major factor in determining annual costs per user and is a significant trade-off parameter optimizing satellite and earth terminal requirements. In the broadcast services, this parameter increases in importance as the network size increases producing lower costs per user, higher satellite power, and smaller earth terminal antennas. In the two direct to the user broadcast cases depicted in Table 4-1, four signals (one per time zone) access the satellite and serve the entire nation regardless of the size of the ground network. In the other cases, it is expected that the number of signals accessing the satellite grow modestly as the size of the ground network increases. Consequently, the expansion in terminals per satellite signal, (as the ground network becomes bigger), is less rapid than in the two direct to the user services.

The Ku-band ground terminals, displayed in Table 4-1, list antennas having diameters ranging from about 1.5 meters to 9.9 meters. Antennas up to 2.4 meters are fixed pointed. Larger antennas up to 4.5 meters have a manual steering capability while still larger antennas are autotracked. Ku-band receivers range from uncooled paramps (i.e., $120^{\circ}K$ to $300^{\circ}K$) to diode mixers (i.e., $950^{\circ}K$ to $5000^{\circ}K$). At intermediate temperatures, (i.e., $300^{\circ}K$ to $950^{\circ}K$), GaAs FET low noise receivers are good choices. If increase in satellite and ground terminal costs of 10% are tolerated and the additional satellite antenna gain into the Southeast is eliminated (See Sections 3.2 and 4.2), the ground terminal parameters can be reduced significantly. The resultant reduced parameters are depicted in Table 4-2. As shown, the maximum antenna diameter can be reduced to about six meters. A GaAs FET receiver is compatible with the most stringent noise temperature requirements.

Table 4-2 Minimum(1) Ku-Band Terminal Configurations

Parameter	Service (2)				
	TV for Retransmission	TV Direct to User	FM Voice/Music for Retrans.	Compressed Bandwidth TV	FM Voice/ Music Direct to User
Antenna Dia. (Meters)	5.8	2.6	1.8	2.1	1.2(3)
Receiver Noise Temp ($^{\circ}$K)	450	700	2190	1730	3100(3)

Notes: (1) Based on allowing 10% increase in minimum satellite/terminal costs and eliminating the additional satellite antenna gain into the Southeast.

(2) Service configurations correspond to those indicated in Table 4-1.

(3) A reduction in G/T from the minimum cost point is not possible since maximum satellite power is used without optimizing the system.

The S-band antenna diameters, displayed in Table 4-1, range from about 0.3 meters to 4.7 meters. All of these antennas are fix pointed. S-Band receivers range from GaAs FET low noise receivers (i.e., 100°K to 1000°K) to diode mixers (i.e. 1000°K to 5000°K devices). In general, S-band antennas are smaller than corresponding Ku-band antennas and higher performance receivers are required. These results are due to lower link margins required at S-band and the availability of inexpensive receivers. They do not take the CCCIR satellite flux density limitations into consideration. When the flux density limits are applied, the system performance parameters and costs are as shown in Table 4-3. When the costs of Table 4-3 are compared with the Ku-band costs of Table 4-1, it is seen that S-band costs range from slightly more than Ku-band costs to significantly less. In particular, the costs are about 50% of the Ku-band costs for the "TV Direct to the User" service. Further, when the S-band antenna diameters of Table 4-3 are compared with the Ku-band antenna diameters of Table 4-4, it is seen that S-band diameters range from slightly more than Ku-band diameters to slightly smaller. Further, S-band TV service can be supplied with fixed pointed antennas. A conclusion is that S-band is attractive for broadcast services.

The UHF ground terminal parameters, displayed in Table 4-1, are reasonably similar to the corresponding S-band parameters. However, in this case the antenna technology is also inexpensive so that slightly larger antennas and lower performance receivers are more optimum. There is no satellite frequency allocation at UHF; therefore, there are no flux density limits to be considered.

Table 4-3 S-Band System Parameters at Flux Density Limit

Service(1)	Gnd Term. Conf. Ant. Dia. (M)	Gnd Term. Conf. Rec'v'r Temp. (°K)	Sat Config. No. Sigs./ Chan.	Sat Config. Pwr./ Chan. (W)	Ave. Sys. Cost/Term. Total Per Year	Ave. Sys. Cost/Term. Total Per Month
TV for Re-transmission(2)	4.7	160	1	4	$39K	$3.3K
TV Direct to User	2.4	275	1	20	$1.1K	$95
FM Voice/Music for Retrans.	2.3	660	64	30	$1.1K	$95
Compressed Bandwidth TV(2)	1.8	510	3	20	$6.7K	$560
FM Voice/ Music Direct to User	1.9	550	20	5	$225	$19

Notes:

(1) Service configurations correspond to those in Table 4-1.

(2) The flux density limit was not reached for the system configuration considered.

Table 4-1 indicates that four beam (i.e. time zone coverage) satellite antenna patterns are preferred on all broadcast services, because of regional requirements. If one signal must be transmitted simultaneously to all ground stations across the country, a one beam U.S. coverage satellite antenna pattern is the most effective system configuration. Even with regionalized transmission requirements the four beam design is only advantageous to Ku-band systems. At S-band and UHF it is found in most cases, (See Section 4.3) that there is little cost difference between the two approaches. Particular Ku-band advantages are due to the feasibility of using multiple feed antennas to effectively shape time zone coverages and due to the lighter weight of Ku-band channelization hardware.

As in the interactive systems, variations in the satellite channel bandwidth are used to change the number of signals sharing a satellite channel. This varies the satellite channel power in order to identify the minimum cost system. Results are similar to those obtained for the interactive systems in that optimized system costs

tend to be inflated as long as satellite channel power requirements are less than 10 to 20 watts. However, results here are different because it is possible in many cases to widen the bandwidth and increase satellite channel power requirements such that the satellite capability s exceeded. In such cases, an optimization relative to the ground complex did not occur and system costs are again inflated. A "U-shaped" system cost trend is often experienced as the satellite channel bandwidth is varied. Bandwidths ranged from about 2MHz to 36MHz. Notice that since the variations are simply a satellite power and cost allocation "tool", the lower bandwidths don't have to represent real satellite hardware implementation. Wideband channels (e.g. 36 MHz) can be used with all of the power allocated to a limited number of signals occupying a limited portion of the available bandwidth.

In general, the number of signals per channel displayed in Table 4-1 represent a wide band satellite channel when the network size is small (e.g. 10^2 to 10^4 terminals) and a narrow band channel when the network size is large (e.g. 10^4 to 10^6). Of course, the RF bandwidth of the user signal is another important factor determining the satellite channel bandwidth and the number of signal accesses per channel. At the wider signal bandwidths, the satellite channel bandwidth requirements are larger and the number of accesses per satellite channel is smaller.

The optimum satellite transponder power is a function of the required link carrier-to-noise (i.e. C/N) ratio, the number of terminals per satellite carrier, the number of carriers per satellite transponder, the bandwidth of each user signal and the number of satellite beams. Maximum power is required only when one U.S. coverage beam is assumed and all other parameters are at or near their maximum values. Of the power levels displayed in Table 4-1, only those associated with the "TV for Retransmission" and "FM Voice/Music Direct to the User" services represent values which may not be the most appropriate. In the first case, the level is too low indicating an inefficient satellite design. In this case, consideration of transponder bandwidths wider than 36 MHz may be appropriate. In the second case, the required power level is too high, representing a situation where not enough satellite power is available to allow a cost optimization. The consideration of transponder bandwidths narrower than 2 MHz may be appropriate for this case.

The costs displayed in Tables 4-1 and 4-3 appear to be reasonable except for those associated with the "Compressed Bandwidth TV" service. However, when the monthly costs are reduced to costs per individual serviced they are modest. It must be remembered that in the retransmission services a large community of users is served by each ground terminal. Further, in the "TV Direct to the User" service each terminal serves one or perhaps several student classrooms. The "Compressed Bandwidth TV" service is too costly based on the cost of the "TV Direct to the User" service. The difficulty lies in the cost of the TV signal encoding/decoding equipment. This technology is still evolving and may become more cost effective in the future. However, for the present and near future it appears to be too expensive for application to a broadcast service. The cost savings from reduced link performance requirements are not sufficient to offset the signal processing equipment costs. The costs of the "FM Voice/Music Direct to the User" service appear to be borderline. Each terminal probably serves a limited number of individuals and only a radio service is supplied.

The distribution of costs between system elements shown in Table 4-1 is variable. When the ground network size is small and/or the user signal power per bandwidth is high, the satellite costs tend to be a significant factor in overall system costs. Means of reducing these costs include widening the satellite transponder bandwidths and innovative satellite design and technology (See Section 3 and Table 3-2). When the ground network is large and/or the user signal power and bandwidth requirements are low, the ground terminal costs tend to be a significant factor in overall system costs. Means of reducing these costs include lower frequency operation (e.g. S-band or UHF) and large scale equipment production by industry. Lower frequency operation is particularly effective if satellite flux density limitations are not in affect. However, low frequency operation can be effective in many cases even when such limits are imposed (See Table 4-3). When the ground network is large, the user signal power and bandwidth requirements are low. When the amount of signal processing is high the fixed equipment costs tend to be a significant factor in overall system costs. Means for reducing these costs include volume production by industry, trade-off of baseband signal quality requirements relative to costs, and innovative design of processing equipment (e.g. LSI).

The variation in average annual cost per user as a function of Ku-band link outage and the means for handling differences in rain attenuation across the country were analyzed for the broadcast services. These considerations are similar to those for the interactive services. However, in this case the receive system noise temperatures of interest are of the range of 300°K to 3000°K. Consequently, noise due to rain attenuation does not have a significant impct on results and has not been considered in the link calculations. This has the effect of reducing the propagation outages at which rain margin starts to significantly impact the cost of the system by a factor of about two. Other than that the conclusions are similar to those indicated in Section 3.1.A.

B. SCOPE OF THE SYSTEM OPTIMIZATIONS

The basic system options considered in the trade off are the satellite launch vehicle, the probability of link outage, the number of users in a nationwide U.S. network, the number of beams per satellite, the number of user signals accessing a satellite channel, and the frequency band. The range of variation for each parameter is defined in Table 4-4 for each particular service. All possible permutations of the listed parameters, with the exceptions footnoted in the table, are selected and satellite/ground terminal optimizations completed. The optimizations determine the minimum system costs and corresponding satellite transmitter and ground antenna, receiver, and transmitter requirements, resulting in thousands of system optimizations requiring the use of a computer.

C. OPTIMIZATION APPROACH AND SECTION ORGANIZATION

The system optimizations are accomplished in a series of three major computerized routines. These are: (1) the satellite cost per transponder versus power per transponder (2) the ground terminal cost versus G/T, and (3) the average annual cost per user versus satellite and ground terminal performance. After the system options are selected, the output relationships from the first two routines are read into the last (i.e. the system optimization routine) to allow the satellite versus

Table 4-4. Basic System Options Subjected to Satellite/Ground Complex Tradeoffs

Service	Options Considered					
	Freq. Band	Launch Vehicle	Link Outage[2]	No. of Term	No. of Sat. Beams	No. of User Sig./Sat. Chan.
TV for Retransmission	Ku S	Delta 2914[1] Delta 3914[1] Atlas Centaur Shuttle 3914[1] Shuttle A/C Ded. Shuttle	1% 0.25% 0.1% 0.075% 0.05% 0.025% 0.01%	10 10^2 10^3 10^4 10^5	1	1
TV Direct To User	Ku S UHF	Same as Above	Same as Above	10^3 10^4 10^5 10^6 10^7 10^8	Same as Above	Same as Above
FM Voice/Music for For Retransmission	Ku S	Same as Above	Same as Above	10 10^2 10^3 10^4 10^5	Same as Above	8 32 64 128
Compressed Bandwidth TV	Ku S	Same as Above	Same as Above	Same as Above	Same as Above	1 2 3
FM Voice/ Music Direct To User	Ku S	Same as Above	Same as Above	10^3 10^4 10^5 10^6 10^7 10^8	Same as Above	20 80 160 320

Note:
1) These vehicles are not considered in UHF system optimizations.
2) Link outages are not considered in S-band and UHF system optimizations.

ground terminal trade-offs to be completed. The system optimization routine employs the downlink performance equation to relate the capabilities of the space and ground segments to the system requirements and options selected. While this equation is being satisfied, the allocated satellite cost per user and the average ground terminal costs are totaled. A systematic search, over a reasonable range of satellite and earth terminal capabilities is conducted and the lowest cost system configuration selected as optimum. At Ku-band, the routine handles variations in ground terminal requirements over four major sectors of the country (i.e. the Northeast, Southeast, West and Midwest). At S-band and UHF, fixed link margins and fixed satellite antenna gains can be applied to all areas of the country. As a result, there is no change in ground terminal G/T with location. Outputs of the routine for the optimum configuration include: average annual cost per user, satellite power, number of satellite transponders required, percent of the satellite payload consumed and earth terminal G/T, receiver and antenna required in each area of the country. Fixed item costs are then manually added to satellite and ground terminal costs.

The receive-only system optimization routine is similar to the transmit / receive system optimization routine, described in detail in Section 3.4. Of course, there is no uplink performance equation to consider. The downlink equation is :

$$(C_T/N_o)\ (1 + B) \quad = (P_{SC}\ B_S G_{SD}/\ LB_{SC} M_{BD})\ (C/4\pi Rf)^2 (G_g/K\ T_g M_D)$$

where:

- f is 12GHz at Ku-band, 2.54 GHz at S-band, and 665 MHz at UHF
- L is 1.259 at Ku-band and 1.122 at S-band and UHF.
- B is assumed to be 1/10.

All other parameters are as defined in Section 3.4.A. The cost equation remains the same. The Ku-band ground terminal cost per location is the same except that there is no ground terminal EIRP (i.e. E_g and $\Delta\ E_g$), uplink margin (i.e. Mu) or uplink satellite antenna gain (i.e. G_{SU}) to consider. The system parameter search is identical except that E_g is no longer involved. The bounds on Ku-band G/T for the reference link (i.e. the Northeast) are $-5\ dB/^oK \leq G/T \leq 39\ dB/^oK$. The bounds applicable to all S-band and UHF links are $-19\ dB/^oK \leq G/T \leq 26\ dB/^oK$ and $-30\ dB/^oK \leq G/T \leq 12\ dB/^oK$, respectively. The performance bounds on the antenna and receiver curves used to generate the G/T versus cost curves are as defined in Table 4-5. Input constants for Ku-band antenna gain and link margin are the same except no uplink inputs are required. The other input constants are as defined in Tables 4-6, 4-7, 4-8 and 4-9. The outputs are the same except that earth terminal EIRP and XMIT PWR are not a consideration.

The receive-only earth terminal computer routine employes antenna and receiver costs versus performance curves, described in Section 3.6, to generate the optimized ground terminal cost versus performance curves. The cost of antenna and receiver combinations satisfying the G/T requirements are totaled. A systematic search, over a reasonable range of subsystem capabilities, is conducted and the lowest

TABLE 4-5 Performance Bounds on Component Curves Used to Generate G/T vs. Cost Curve

Frequency	Ant. Gain		Rec'vr. Temp.*	
	Min.	Max.	Min.	Max.
Ku-Band	28.7 dBi	71 dBi	18 dB	43dB
S-Band	15.3 dBi	58.3 dBi	18dB	43dB
UHF	9.5 dBi	45.0 dBi	18.5dB	43dB

*Total System Temperature in dB Relative to 1°K.

TABLE 4-6 Service Related Performance Cost Parameter Selections

SERVICE	C/No. (dB)			Signal Bandwidth (MHz)	Sat. Chan. Bandwidth (MHz)	Back-off	Configuration	Type Signal
	Ku-Band	S-Band	UHF					
TV for Retransmission	86.8	87.1	-	32.0	32.0	0dB	Redundant	Analog
TV Direct to the User	85.2	85.4	85.4	22.0	22.0	0dB	Non Redundant	Analog
FM Voice/Music for Retransmission	60.6	61.0	-	0.24	1.92 7.68 15.36 30.72	5.1dB	Redundant	Analog
Compressed Bandwidth TV	73.5	73.5	-	12.0	12.0 24.0 36.0	0 dB 1.6dB 5.1dB	Non Redundant	Digital
FM Voice/Music Direct to User	57.0	57.5	57.5	0.1	2 8 16 32	5.1dB	Non Redundant	Analog

TABLE 4-7 S-Band & UHF Margin Requirements

Frequency	Margin* Applied to	
	Analog Sys.	Dig. Sys.
S-Band	3dB	2dB
UHF	4dB	-

*Margin is not varied as a function of link outage at UHF and S-Band.

TABLE 4-8 S-Band & UHF Satellite Downlink Antenna Gain*

Frequency	Antenna Gain (dB)	
	U.S. Coverage	Time Zone Coverage
S-Band	29.5	32.5
UHF	29.5	32.5

*Gain does not change with location in the country.

TABLE 4-9 Ground Complex and Satellite Channel Access Pairing

No. of Term.(s)	TV For Retransmission		TV Direct To User		FM/Voice Music for Retransmission		Compressed Bandwidth TV		FM Voice/Music Direct to User	
	NTC	NSC	NTC	NSC	NTC	NSC	NTC	NSC	NTC	NSC
10	10	1	-	-	10	1	10	1	-	-
10^2	25	4	-	-	25	4	25	4	-	-
10^3	250	4	250	4	125	8	125	8	250	4
10^4	1250	8	2,500	4	625	1	625	16	2,500	4
10^5	6250	8	25,000	4	3125	32	3125	32	25,000	4
10^6	-	-	250,000	4	-	-	-	-	250,000	4
10^7	-	-	2,500,000	4	-	-	-	-	2,500,000	4
10^8	-	-	25,000,000	4	-	-	-	-	25,000,000	4

cost combination selected as optimum. This routine can provide optimizations for both redundant and non-redundant versions of the receiver. It is essentially identical to the routine discussed in detail in Section 3.5 except that the transmitter and ground terminal EIRP are not involved. The receive-only terminal costs versus G/T curves are provided in Appendix 7.

The satellite routine is summarized in Section 3.1.C and discussed in detail in Section 3.7. The latter discussion deals with both broadcast and transmit/receive satellite cost and performance relationships. The only difference is that batteries sufficient to maintain communications operation during eclipse are not provided for broadcast satellites.

The output of the receive-only system optimizations is summarized and analyzed at length in Sections 4.2 and 4.3. Section 4.2 examines cost variations as a function of Ku-band link outage. The results are almost identical for all services eliminating the need for a detailed service by service evaluation. The remaining results are evaluated service by service in Section 4.3. The format, for each service, involves considering in order: (1) annual cost versus satellite transponder bandwidth, (2) annual cost versus number of beams per satellite (3) satellite performance requirements, (4) satellite and ground terminal cost versus network size, (5) ground terminal performance requirements, and (6) total system costs. In the "TV for Retransmission" and "TV Direct to the User" services, cost versus satellite transponder bandwidth is not a consideration.

4.2 AVERAGE ANNUAL COST VS. PERCENT Ku-BAND LINK OUTAGE

Satellite and ground complex cost versus link outage trends vary little from one receive-only service and system configuration to another. Other services having bandwidths of 32 MHz, 22 MHz, 240 KHz and 100 KHz are examined along with a 6 Mbps digital service. One and four-beam satellites ranging in size from a Delta 2914 to a Dedicated Shuttle payload are considered. Ground networks from 10 to 10^8 terminals are evaluated. The similarity of all results is depicted in Figures 4.-1, 4-2, 4-3, and 4-4. These figures are chosen to bound the system options considered. The full set of system costs versus link outage curves are given in Appendix 7.

As shown, there is an almost negligible cost increase as the link outage decreases from 1% to 0.1%. Cost increases do not become significant until link outage decreases to 0.05%. As the outage requirements decrease further, system costs rise rapidly and become totally unreasonable at an outage of 0.01%. These results are in general agreement with those described in Section 3.2 for the interactive services. However, in the interactive case, the system noise contributions due to rain attenuation are significant. This causes the outages, at which system costs start to be impacted by rain margin, to be higher by a factor of about two (i.e., 0.1% instead of 0.05%). Once again, average costs means that costs of the terminals in the Southeast, Northeast, Central and West sections of the U.S. have been averaged before being combined with the allocated satellite cost per terminal. Further, it is once again observed that factors impacting the cost versus outage trends include:

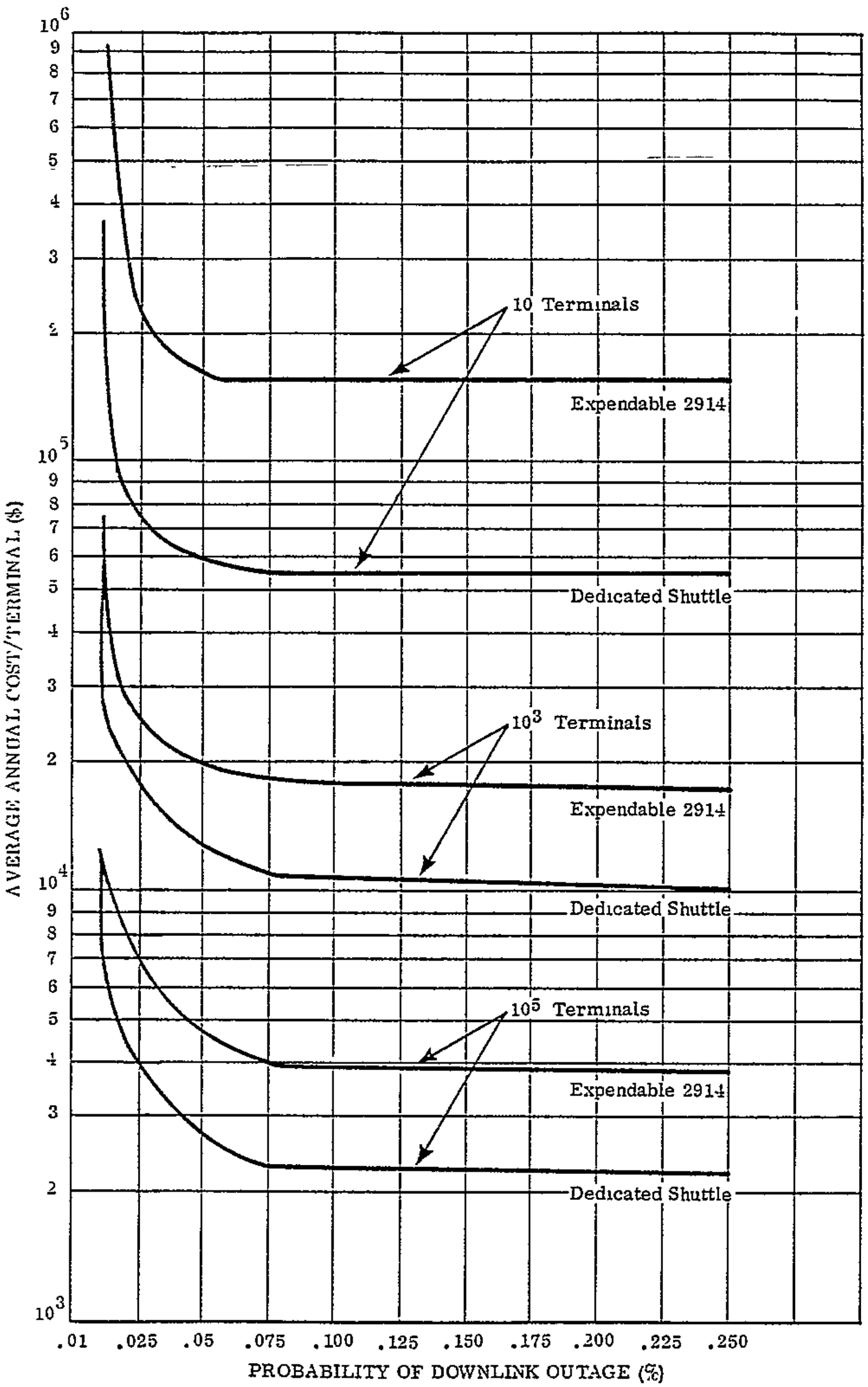

Figure 4-1 Annual Cost Versus Ku-Band Link Outage
(1 Beam Satellite)
(TV for Retransmission)

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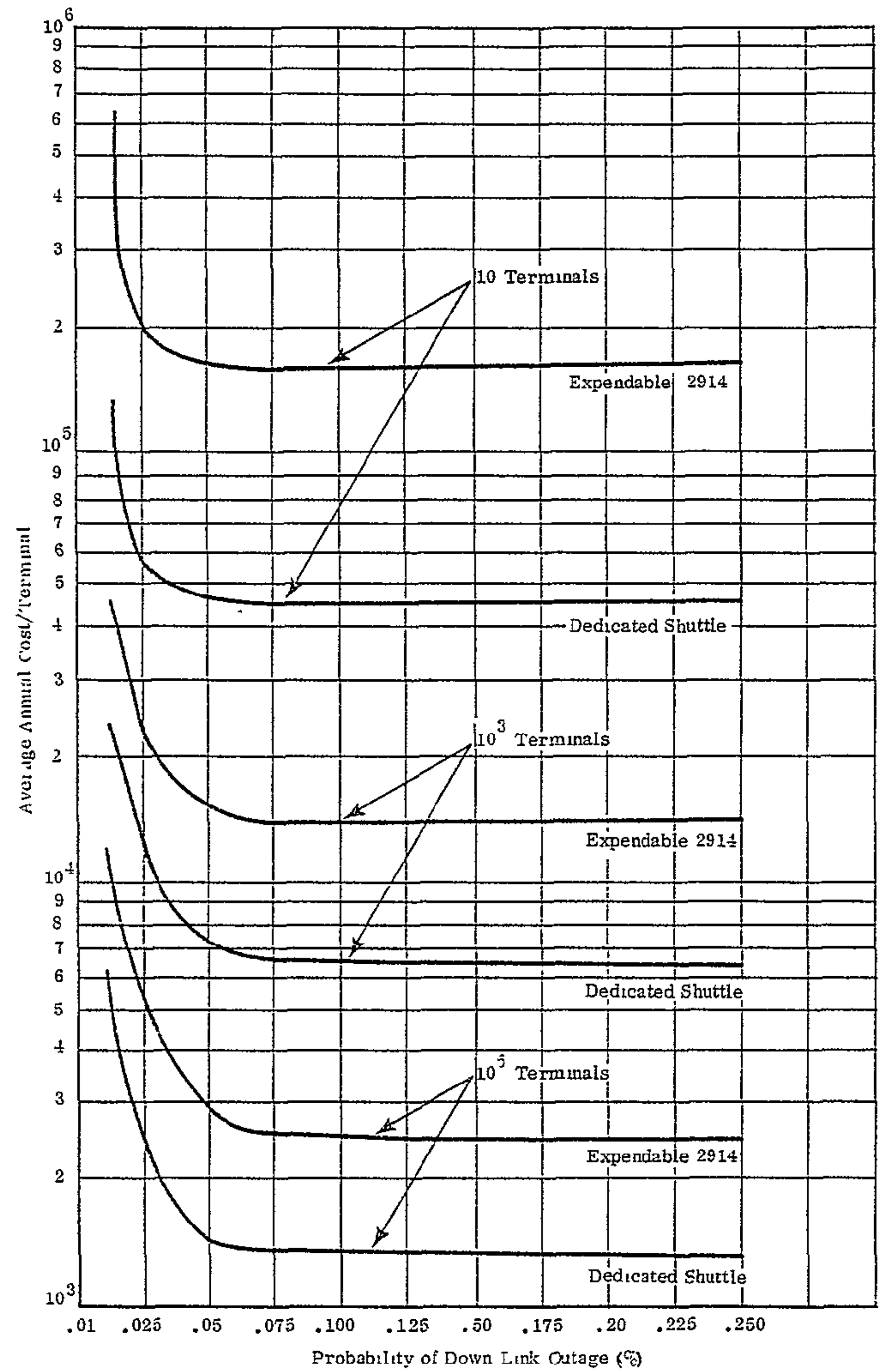

Figure 4-2. Annual Cost Vs. Ku-band Link Outage (4 Beam Satellite)
(TV for Retransmission)

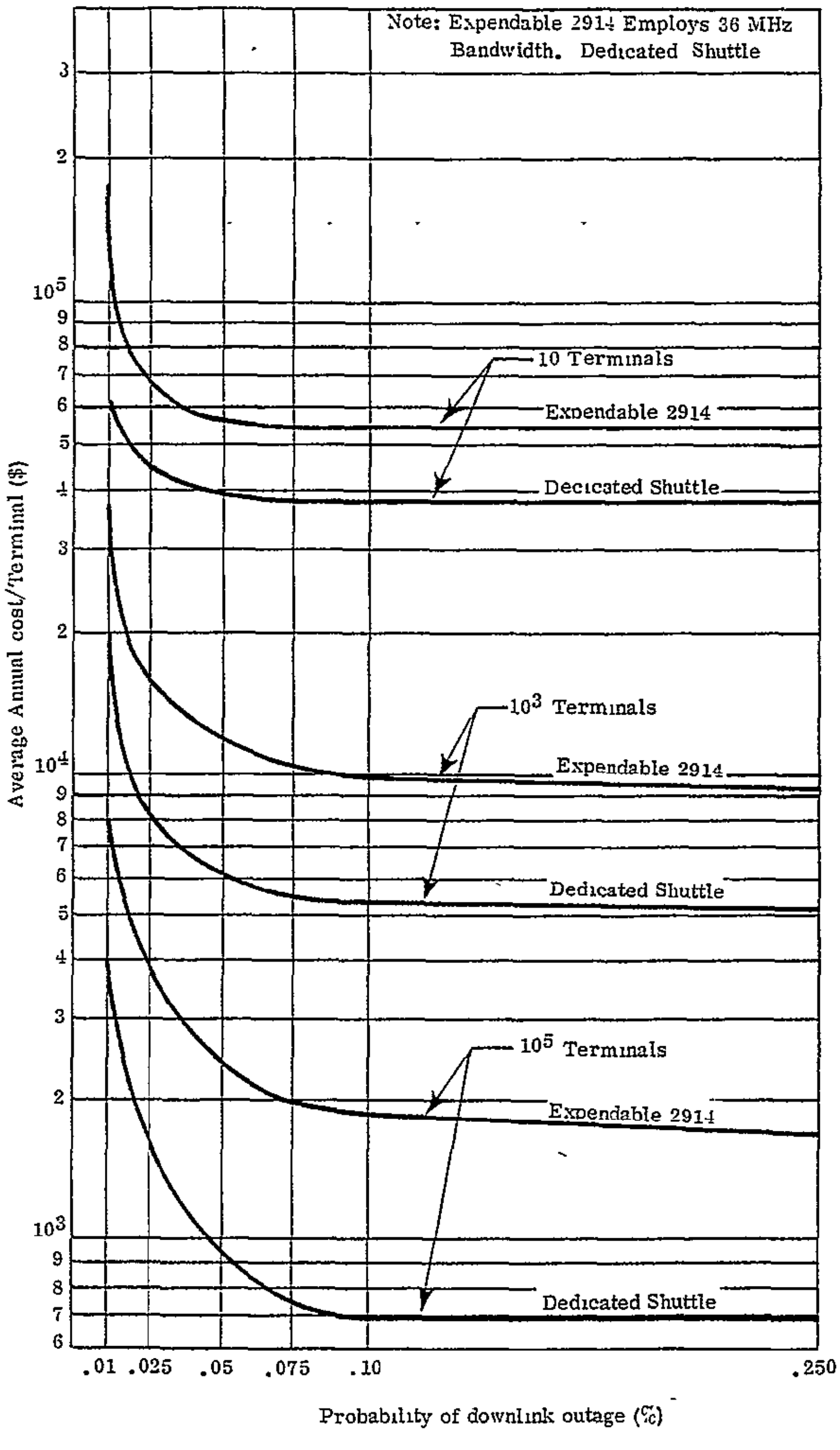

Figure 4-3 Average Annual Cost vs. Ku-Band Link Outage (1 Beam Satellite) (Compressed Bandwidth TV)

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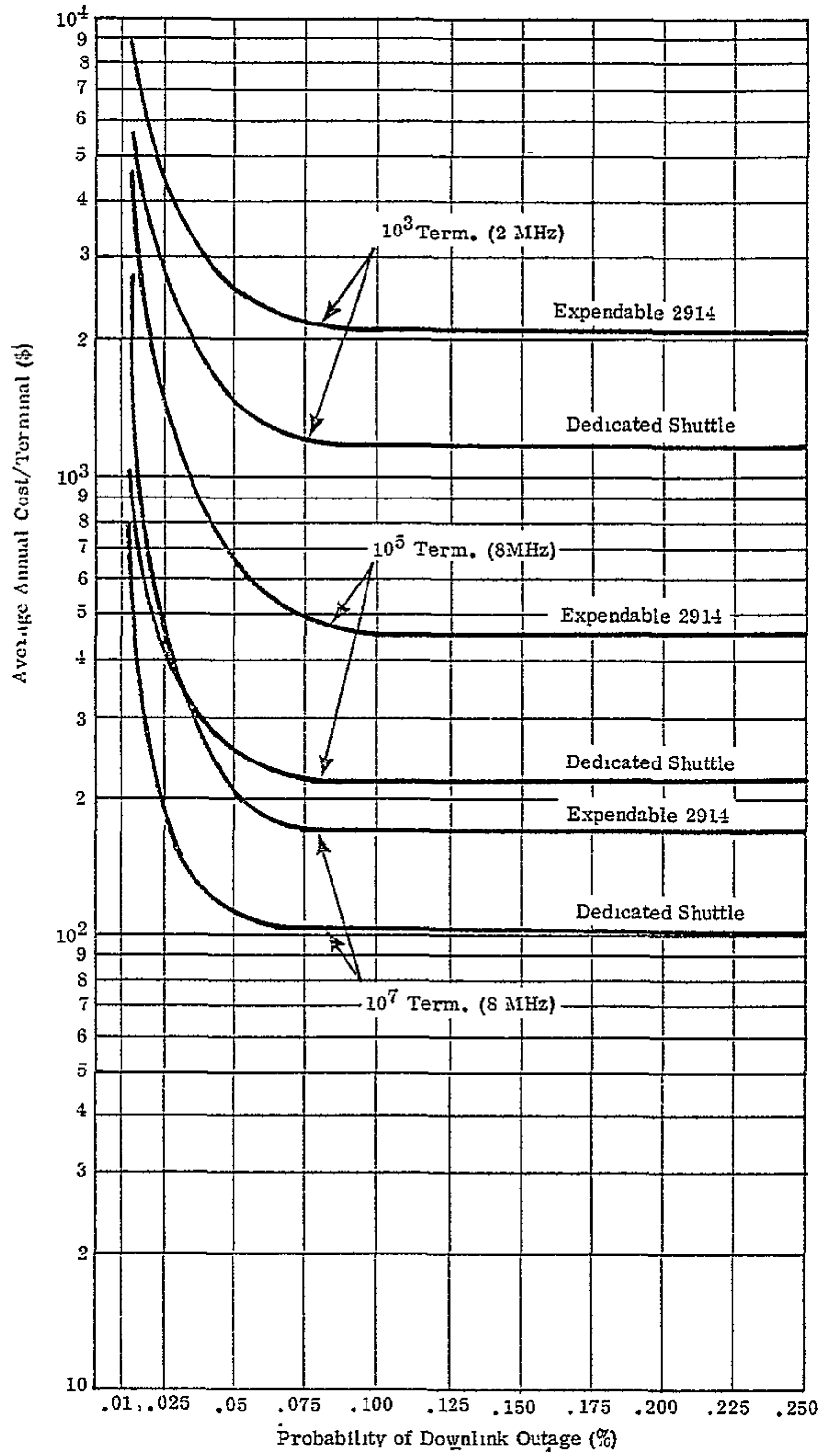

Figure 4-4. Average Annual Cost/Terminal vs Probability of Downlink Outage (Ku-Band, 1 Beam Satellite) (FM Voice/Music Direct to User)

- Rain attenuation versus outage
- Minimum margins necessary to establish clear sky requirements
- Differences in minimum margins applied to digital and analog services
- Variation in rain attenuation and rain margin requirements from one section of the country to another. (See Section 3.2 for a further discussion of these factors and their influence on the annual cost versus link outage trends.)

Observations worth emphasizing are those associated with designing systems to handle the differences in Ku-band rain attenuations across the country. It is concluded that equal satellite antenna gains and identical ground terminals can be used in all areas of the country when the link outages required are 0.5% or greater. For outages between 0.5% and 0.05%, unequal satellite antenna gains are cost-effective in countering the effects of differences in rain attenuation. At lower outages, the higher satellite antenna gain offsets the need to be compensated by variations in the ground terminal capabilities. Finally, at a system outage of 0.01%, it may be necessary to accept slightly poorer performance in the Southeastern U.S.

4.3 SYSTEM PERFORMANCE/COST TRADE-OFFS

A. TV FOR RETRANSMISSION

1. Average Annual Cost Vs Number Beams Per Satellite

The same basic cost comparisons between the one-and four-beam satellite design, observed for the transmit/receive services, also pertain to receive-only systems. The major difference is that traffic requirements can be regionalized by time zone. If one broadcast signal is distributed across the country to all terminals, there can be no advantage in employing four beams since four satellite channels are required instead of one. However, if the requirement is for four channels broadcasting to four time zones, then the four-beam satellite has a potential advantage since four channels are required on both the one and four beam satellites. Consequently, the regionalized broadcast scenario is adopted for all receive-only services. System cost comparisons between the one and four beam Ku-band satellite designs for the "TV for Retransmission" service are displayed in Table 4-10. Additional cost comparisons and similar ones for S-band satellites are presented in Appendix 7.

Table 4-10 shows that for a small ground network, the four-beam approach is the most effective only for satellites larger than a Delta 3914. In contrast, it is the most effective for all satellite sizes considered when the ground network is large. Notice that the required satellite power per channel is small for the small network and large for the large networks. A low satellite transponder power implies a large number of transponders and a major percentage of the available communications payload consumed in filters, frequency converters, and transmitter drivers. In such a case, the weight penalty for four receivers and antenna feeds for the time zone design can be signficiant and the smaller the satellite the more signficiant the penalty.

Table 4-10. Average Annual Cost/Terminal Vs. Number of Beams/Satellite (Ku-Band Satellite) (TV Distribution)

No. of Beams	Launch Vehicle	.1% OUTAGE		.05% OUTAGE	
		10 Term.	10^5 Term.	10 Term.	10^5 Term.
	Exp. 2914	153,855.	3,935.	159,520.	4,745.
	Exp. 3914	130,945.	3,625.	135,920.	4,480.
1	Shuttle 3914	108,605.	3,315.	112,890.	4,030.
	Exp. A/C	91,130.	3,035.	95,195.	3,670.
	Shuttle A/C	76,410.	2,815.	79,955.	3,320.
	Ded. Shuttle	56,675.	2,330.	59,325.	2,740.
	Exp. 2914	163,565.	2,595.	165,735.	2,965.
	Exp. 3914	127,995.	2,335.	130,750.	2,630.
	Shuttle 3914	105,575.	2,190.	108,080.	2,420.
4	Exp. A/C	79,440.	1,890.	81,695.	2,050.
	Shuttle A/C	66,225.	1,755.	68,385.	1,890.
	Ded. Shuttle	46,290.	1,430.	48,455.	1,530.

These penalties are magnified at S-Band as indicated in Appendix 7. In this case, the receiver, channelization components, feeds and antennas are all considerably heavier. Further, there is a signficiant difference between the weight of the one-and four-beam S-band antennas while the gain advantage for the latter is only about 3 dB. Such a modest difference in antenna patterns is a result of the coverage overlap between the time zone beams; it is less practical to shape the antenna patterns at S-band than at Ku-band. See Section 3.3.A.1 for a discussion of the beam shaping available at Ku-band through the use of multiple antenna feeds. The resultant difference between the one-and four-beam antenna gains is 5.5 dB. With these facts in mind, the 4-beam configurations are selected for examples on all Ku-band systems. However, large satellites operating with large networks are considered for S-band systems, so that one beam system is applicable.

2. Satellite Requirements

The coinciding increases in satellite power per channel and ground network size indicated above, is verified in Figure 4-5 for a Ku-band satellite. A similar trend is displayed for the S-band satellite in Appendix 7. As the number of terminals receiving a single broadcast signal from the satellite increases, the satellite cost per terminal decreases. This makes it cost-effective to increase satellite transmitter output and decrease the terminal G/T. The figures indicate the increase in the power per channel as the satellite becomes larger is a result of a corresponding reduction in the cost of power. As shown in Appendix 7, this pattern is disrupted at S-band by the selection of single beam antennas for the smaller satellites (i.e., Expendable 2914 and Shuttle 3914 payloads) which results in comparatively higher satellite power in order to compensate for the loss of satellite antenna gain. As a result, the one beam small satellite power curves overlap the four-beam large satellite (i.e., Shuttle Atlas-Centaur and Dedicated Shuttle payload) power curves. However, the power increases are not as rapid as might be inferred by the increases in network size. because the scenario adapted for system growth includes an increase in the number of satellite channels as the network increases. It is unlikely that the redistribution systems in the country will use only four network channels. Accordingly, Figure 4-5 shows that the number of satellite channels required is, one for a network of 10 terminals, four for 10^2 and 10^3 terminals, eight for 10^4 terminals, and 16 for 10^5 terminals. One wideband satellite channel is employed per signal access.

Figure 4-5 also indicates that the percentage of satellite payload consumption is quite modest until the network approaches 10^4 terminals. At 10^5 terminals more than one small to intermediate size satellite or almost all of a Dedicated Shuttle satellite is required. This is understandable since 16 channels with power requirements on the order of 40 to 150 watts per channel must be provided. Reasonable network sizes, in the period before 1985 are anticipated to be between 10^2 and 10^4 terminals. Accordingly, a Shuttle Atlas-Centaur sized satellite is a reasonable selection.

The Ku-band coordination limits displayed can be read directly from the four-beam satellite curve shown in Figure 3-5. Satellite backoff is not a factor since there is only one signal per channel. Further, the effective bandwidth over which signal power is spread is about 27 MHz even though the channel bandwidth employed is 32 MHz. This means no adjustments have to be made to the curve.

S-band power at the flux density limit, shown in Appendix 7, is determined as follows. The basic CCIR requirement applicable to the 1 GHz to 10 GHz segment of the frequency spectrum is:

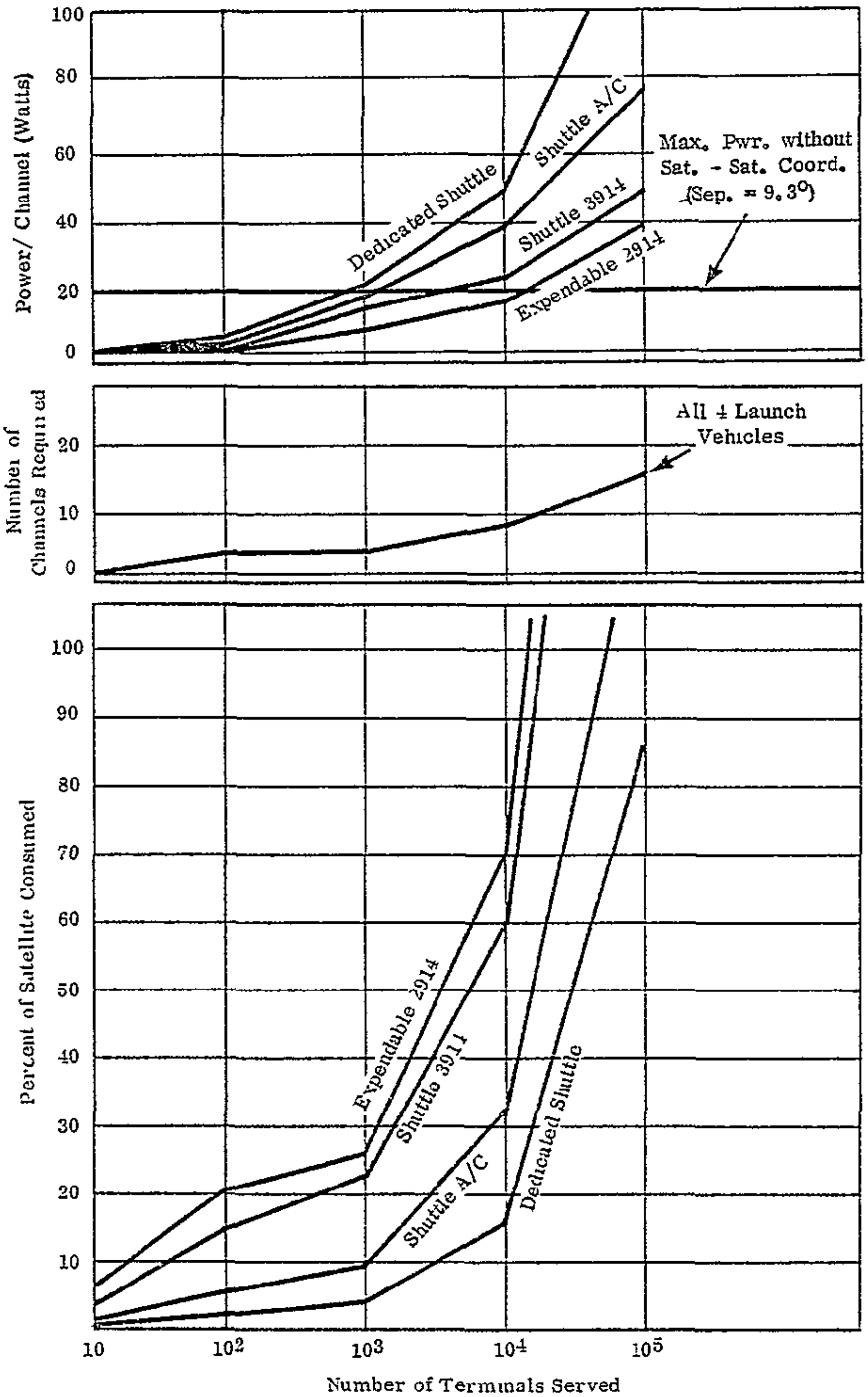

Figure 4-5 Satellite Power and Capacity Requirements
(Ku-Band, 4 Beam Satellite 1% Outage)
(TV Distribution)

$$Es\ (dB) = -152 + \theta/15\ (dBW/M^2)\ \text{in any 4 KHz channel}$$

where:

- Es is the allowable flux density at the surface of the earth in dBW/M^2
- θ is the satellite elevation angle at the earth terminal in degrees above the horizon and 7.5^o is taken as a worst case requirement.

This translates into the following EIRP/signal, Ep, requirement at the satellite:

$$Ep\ (dBW) + \log_{10}\left(\frac{1}{4\pi R^2}\right) -10 \log_{10} \left(\frac{W + Bs'}{4 \times 10^3}\right) = -151.5$$

- R is the slant range from the satellite to the earth terminal
- W is the bandwidth over which signal power is dispersed as a result of the spreading waveform employed.
- B_s^1 is bandwidth, (i.e., 1 MHz) over which signal power is dispersed as a result of the audio subcarrier added to the baseband TV signal

This further translates into the following satellite power per channel, Psc (displayed on the S-band satellite requirement curves.):

$$Psc\ (dB) = 11.5 + 10 \log_{10}\left(\frac{W + 1}{4 \times 10^3}\right) -5 \log_{10} \left(\frac{32 + W}{32}\right) - G_s + M_{B0} + 10 \log_{10} \frac{Bsc}{Bs}$$

where:

- Gs is the edge of coverage gain (i.e., 3 dB down from peak). It is 32 dB for a 4-beam S-band antenna and 29 dB for a 1-beam S-band antenna.
- Ls is the loss between the satellite transmitter and the antenna feed. It is 0.5 dB for the S-band satellite.
- $5 \log_{10}\left(\frac{32 + W}{32}\right)$ is one-half the total increase to the link C/N due to the presence of the spreading waveform. It represents an addition to the Psc determined without considering the presence of a spreading waveform. It is allowed to be 0.5 dB in this case, which corresponds to W=8.3MHz of spreading. The other 0.5 dB of increased C/N must be compensated by increasing the derived ground terminal G/T by 0.5 dB.
- M_{BO} is the satellite transmitter output backoff. It is 0 dB in this case.
- $10 \log_{10} (B_{SC}/B_S)$ accounts for the fact that there may be several signals accessing a satellite channel. B_{SC} is the indicated satellite channel bandwidth and B_S is the indicated signal bandwidth. Neither of these values include the expansion necessary if spreading is employed. However, the ratio of B_{SC} to B_S is the same in any case (e.g. =1) for this service. When the appropriate values are inserted in the above equation, it is determined that P_{SC}=21 watts for a 4-beam satellite and 42 watts for a 1-beam satellite.

3 Satellite and Ground Terminal Cost Vs Network Size

The average annual cost per terminal decreases dramatically in broadcast systems as the size of the ground network increases, which is illustrated in Figure 4-6. The reductions are a result of the wider distribution of satellite costs as the number of terminals per signal increases and the increased size of the ground terminal buy. The figure compares the results at both Ku- and S-band. The S-band results do not take the satellite flux density limitations into consideration. As shown, S-band has the potential for providing a considerable cost saving, due primarily to the lower cost of the ground network. For small network sizes (where satellite costs predominate) the S-band system is at a disadvantage because the increased weight of S-band components and the S-band antenna produce a less cost-effective, low power, satellite than is the case at Ku-band.

Imposing the satellite flux density limitations has little effect on the above results. Appendix 7 shows that the flux density limitations become a factor only at a network size of about 10^4. This means in order to be in compliance with the regulations, the satellite power per channel and earth station G/T must be frozen at about 20 watts and 9.25 dB respectively. This does not mean that the cost of the service stays constant as the size of the ground network increases. The satellite cost allocation continues to be spread over a larger number of ground terminals and the size of the ground terminal buy continues to increase. It does mean that the rate of cost decrease is somewhat reduced since the system can no longer optimize. However, when the S-band costs for a 10^5 network are recomputed on this basis, they increase by only about 17%. That is, they increase from $725 per terminal (see Figure 4-6) to $850 per terminal, and this still compares favorably with a corresponding Ku-band cost of about $1,750 per terminal (see Figure 4-6).

4. Ground Terminal Requirements

Variations in Ku-band performance parameters, as a function of increases in the ground network size, are depicted in Figure 4-7. Similar results for the S-band terminals are depicted in Appendix 7. As expected, the G/T changes are counter to the satellite power changes. G/T decreases are accomplished primarily by decreasing the antenna size, however, there are accompanying increases in antenna temperature. The terminal antenna sizes are large while the receiver requirements are moderate. For a network of 10 terminals, a 9.9 meter autotracked Cassegrain and a 265°K uncooled paramp receiver is required. For a network of 10^4 terminals, a 4.4 meter manually steered Cassegrain antenna and a 460°K GaAs FET receiver is required. These results reflect a high performance application with a redundant receiver. Consequently, the G/T requirements are relatively stringent and the burden of meeting them falls primarily on the antenna. Deviations in terminal parameters that increase system costs by no more than 10% are depicted in Table 4-11. The bounding parameters are read from the system optimization curves depicted in Appendix 7. For a Ku-band network of 10^2 terminals, a 23-foot autotracked Cassegrain antenna and a 350°K GaAs FET receiver can be used. For a network of 10^4 terminals, a 13-foot manually steered Cassegrain antenna and a 745°K GaAs FET receiver is satisfactory. It should be noted that these parameters are for a terminal located in the Northeastern U.S.

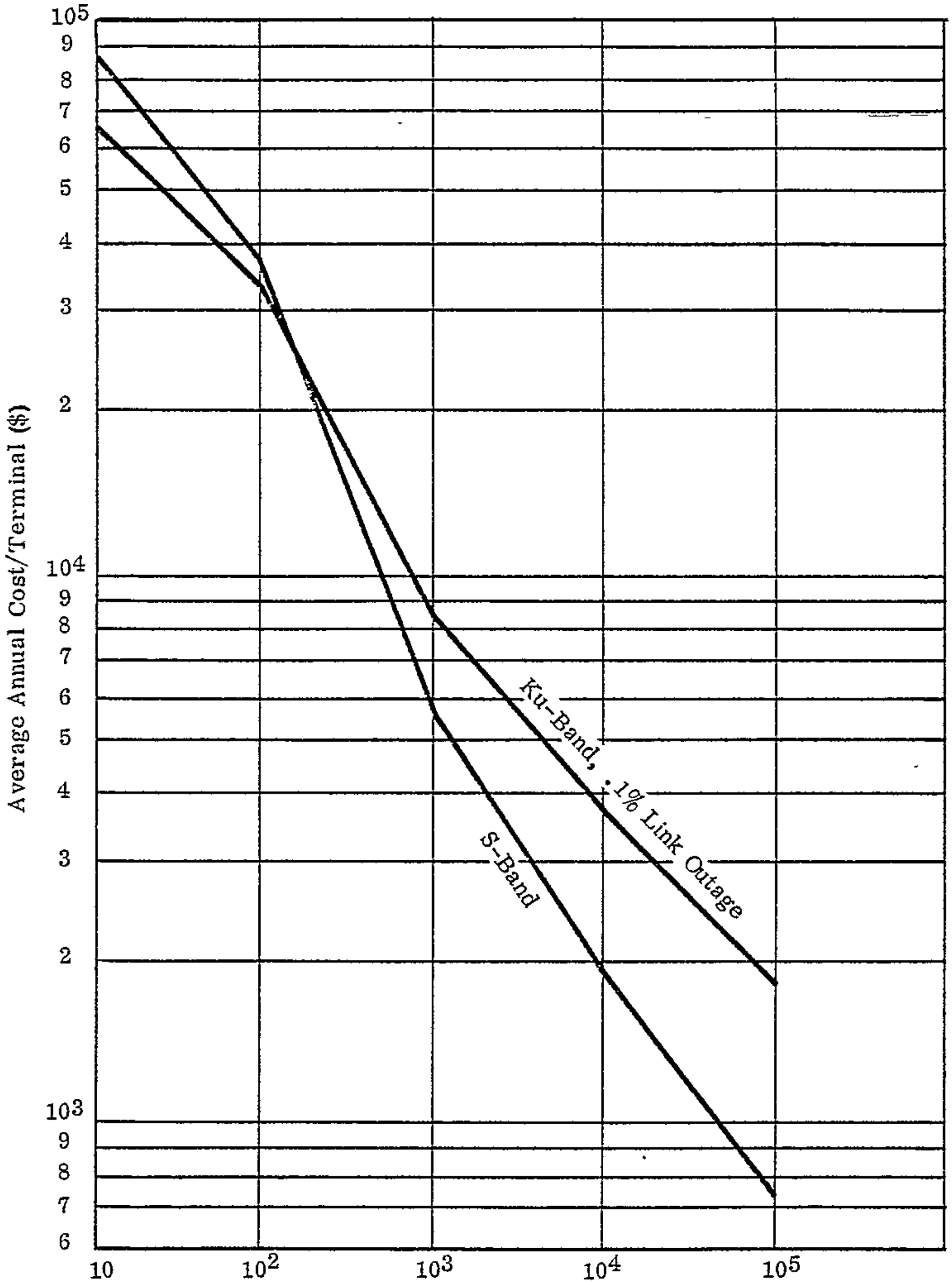

Figure 4-6 Annual Cost vs. Network Size & Frequency Band (Shuttle A/C, 4 Beam Satellite)(TV Distribution)

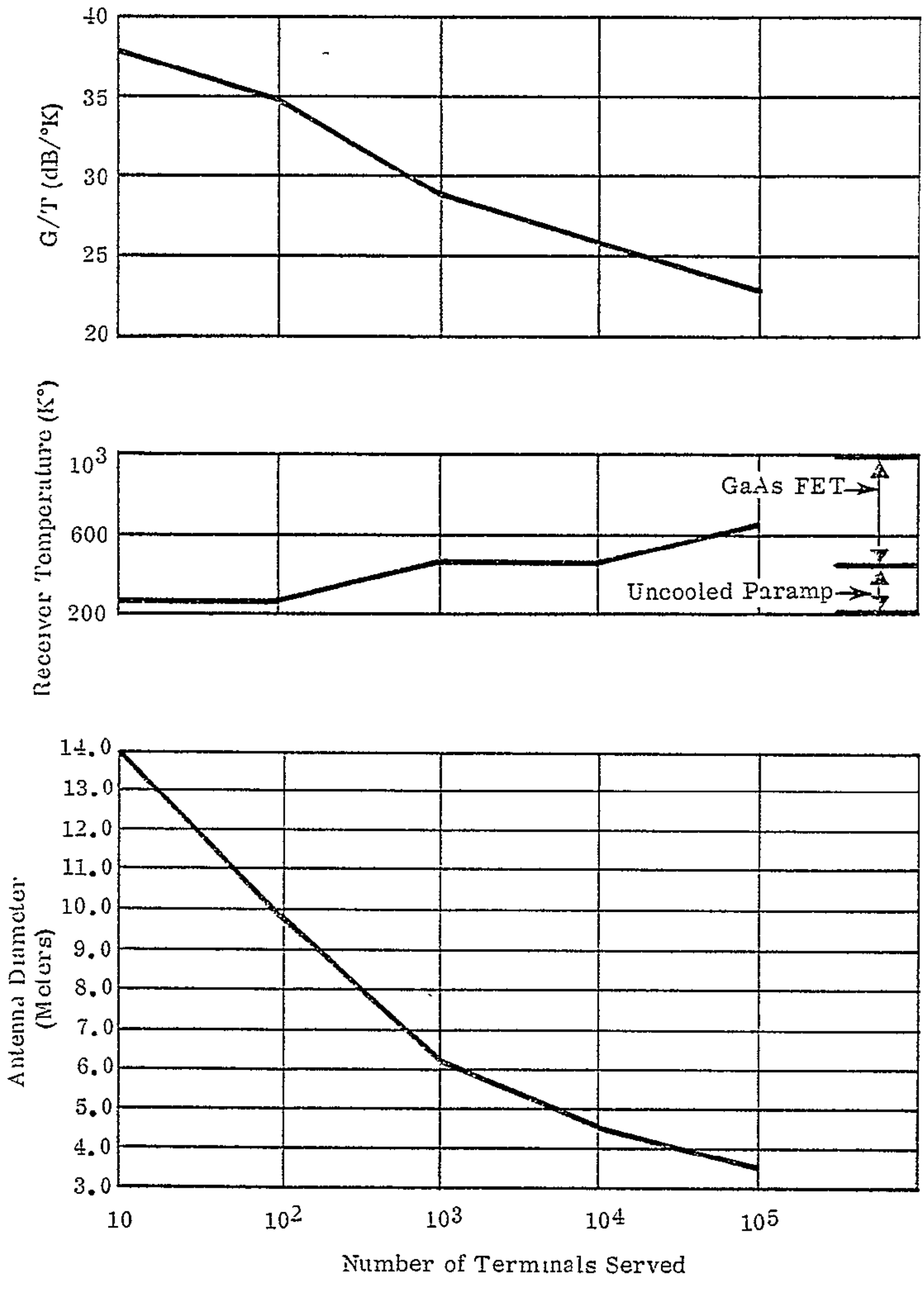

Figure 4-7. Ground Terminal Requirements
(Ku-band. .1% Link Outage, 4 Beam. Shuttle A/C
(TV Distribution)

Table 4-11. Bounds on Ground Terminal G/T, Receiver Temperature and Antenna Diameter (4 Beam Satellite (TV Distribution)

Frequency	Number of Terminals	Parameter	Lower Bound	Upper Bound
Ku-Band .1% Link Outage (1)	10^2	G/T dB/°K	31.	39. (2)
		Receiver Temperature (°K)	350.	265.
		Antenna Diameter (meters)	7.0	15.5
	10^4	G/T (dB/°K	23.	29.
		Receiver Temperature (°K)	745.	580.
		Antenna Diameter (meters)	4.0	7.0
S-Band (2)	10^2	G/T (dB/°K)	12.	25.
		Receiver Temperature (°K)	275.	40.
		Antenna Diameter (meters)	3.5	7.5
	10^4	G/T (dB/°K)	6.	11.
		Receiver Temperature (°K)	275.	160.
		Antenna Diameter (meters)	2.0	2.5

(1) All cases use shuttle A/C launcher.

(2) Represents maximum G/T available.

Further reductions are feasible if the 7 dB of extra Ku-band satellite antenna gain into the Southeast is eliminated. As indicated in Section 3.3.A.4, this results in a 2.5 dB adjustment to the satellite antenna gain in the Northeast and results in a corresponding decrease in the terminal performance requirements. For a network of 10^2 terminals, a 19.0-foot manually steered Cassegrain antenna and a 450°K GaAs FET receiver is adequate. For a network of 10^4 terminals, a 10-foot manually steered Cassegrain antenna and a 950°K diode mixer receiver is adequate.

Table 4-11 also displays S-band terminal parameters corresponding to the Ku-band parameters indicated above. As shown, the antenna diameters are smaller and the receiver temperatures lower, because S-band receiver technology is less expensive than Ku-band receiver technology while the difference in the antenna costs is not large. For an S-band network of 10^2 terminals, a 12-foot fixed pointed, prime focus fed parabolic antenna and a 275°K GaAs FET receiver can be used. No additional adjustments, by eliminating extra satellite antenna gain into the Southeast, are available in this case. The S-band terminal parameters indicated in the table do not take the satellite flux density limitations into consideration. At the flux density limits, a 9-foot antenna and a 275°K receiver is required.

5. Total System Cost Breakdown

Total system cost per terminal, including the fixed performance items, are summarized in Table 4-12. Annual costs for a Ku-band network of 10^2 terminals is about \$35K. This amounts to about \$4.9K per month. If each distribution terminal serves an average of only 3,000 users, the average cost per user per month is less than \$1. As the size of the ground network increases, the system costs drop dramatically. The fixed item costs are entirely equipment costs, which are broken out in detail in Appendix 1. For a network of 10^2 terminals, the average buy is in lots of about 10 and the capital cost is about \$7.5K. When the 0.233 annualizing factor is applied, the yearly costs become \$1.75K.

Table 4-12 indicates that satellite costs dominate the small networks and remain important even in larger networks. Ground terminal costs become important only in the larger networks. This distribution of costs is further verified in the sensitivity analysis. Results of this analysis are discussed in Appendix 7. The analysis considers independent $\pm$ 10 dB variations in link performance, satellite cost, and ground terminal cost with all other factors constant. Table 4-12 also shows that fixed equipment costs are not important in this service.

All this points to concentrating on the satellite in attempting cost reducing innovations. Longer life, higher reliability satellites, shuttle optimized satellites, higher efficiency solar arrays, ion jets, etc. are all of potential benefit. Further,

Table 4-12. Breakdown of Total Average Annual Cost/Terminal (4 beam satellite)/TV Distribution)

Frequency	Number of Terminals	Total Annual Cost (&)	Percent of Total Cost		
			Satellite	Ground Terminal	Fixed
Ku-Band	10^2	34,885.	68	27	5
	10^4	4,145.	33	55	12
S-Band	10^2	39,460	86	10	4
	10^4	2,330.	43	36	21

Note: Shuttle A/C used for all cases.

(based on the results of Section 3), it may be wise to consider wider satellite channel bandwidths with multiple signals per channel for network sizes of about 10^2 terminals. The latter may be particularly helpful in the case of the S-Band satellite. Finally, S-Band is an attractive operative frequency even with the flux density limits applied.

B. TV DIRECT TO THE USER

1.0 Average Annual Cost Vs. Number Beams Per Satellite

The same basic cost comparisons between one- and four-beam satellites, as observed for the "TV for Retransmission" service, pertain to the "TV Direct to the User" service. However, in this case, the network sizes of interest and the satellite power per channel are larger. Therefore, the weight of channelization hardware and antennas is less important and the advantages of the four-beam approach are more prominant. The system cost comparisons between the one- and four-beam Ku-Band satellite designs, are displayed in Table 4-13. Similar cost comparisons are provided for S-Band and UHF satellites in Appendix 7.

The table indicates 4-beam Ku-Band system costs are less regardless of the size of the satellite as long as the ground network includes 10^3 or more terminals. The same is not true at S-Band where, for a network of 10^3 terminals, the four-beam approach enjoys an advantage only for Atlas-Centaur sized payloads or larger. For a network of 10^7 terminals, the four-beam approach enjoys an advantage for Delta 3914 sized payloads or larger. However, in any S-Band system configuration there is little cost difference between the two approaches to satellite design. The same is true for the UHF systems. In the latter case only Atlas-Centaur sized payloads or larger are considered. As a result, the four-beam configuration enjoys a slight cost advantage for all UHF systems considered. With these facts in mind, the four-beam approach has been selected for illustrating Ku-Band, S-Band and UHF system characteristics.

2.0 Satellite Requirements

The same increases in satellite power per channel and ground network size as observed for the "TV for Retransmission" service, exists for this service. The major difference is that the number of terminals per satellite signal and the power per satellite channel is larger. The trend for a Ku-Band satellite is displayed in Figure 4-8. Similar trends are displayed for S-Band and UHF satellites in Appendix 7. Figure 4-8 shows that the maximum power per channel available on Delta 2914 or Shuttle 3914 sized Ku-Band satellites, is reached at a network size of 10^5 terminals. The maximum available on Shuttle Atlas-Centaur sized satellites is reached at a network size of 10^6 terminals. On Dedicated Shuttle sized Ku-Band satellites, it is reached at a network size of 10^7 terminals. In the case of S-Band and UHF systems, corresponding maximums occur at network sizes that are larger by a factor of approximately 10, a result of the higher maximum powers available on satellites operating in these frequency bands (see the satellite cost per channel curves of Section 3.7). All limits are based on four-beam satellites where the minimum number of channels is four.

Table 4-13. Average Annual Cost (Terminal Vs. Number Beams/Satellite) (Ku-band System) (TV Broadcast)

	LAUNCH VEHICLE	0.1% OUTAGE		.05% OUTAGE	
		10^3 TERM.	10^7 TERM.	10^3 TERM.	10^7 TERM.
1 Beam Satellite	EXP 2914	14,495	730	16,640	1100
	EXP. 3914	13,150	605	15,255	945
	SHTL. 3914	11,770	605	13,860	940
	EXP. A/C	10,625	275	12,655	545
	SHTL. A/C	9,635	270	11,530	545
	DED. SHTL	8,175	140	9,740	145
4 Beam Satellite	EXP 2914	11,830	355	12,495	405
	EXP. 3914	10,125	295	10,680	340
	SHUTL. 3914	8,880	295	9,375	340
	EXP. A/C	7,285	180	7,830	185.
	SHTL. A/C	6,405	175	7,000	135
	DED SHTL	5,305	125.	5,670	125.

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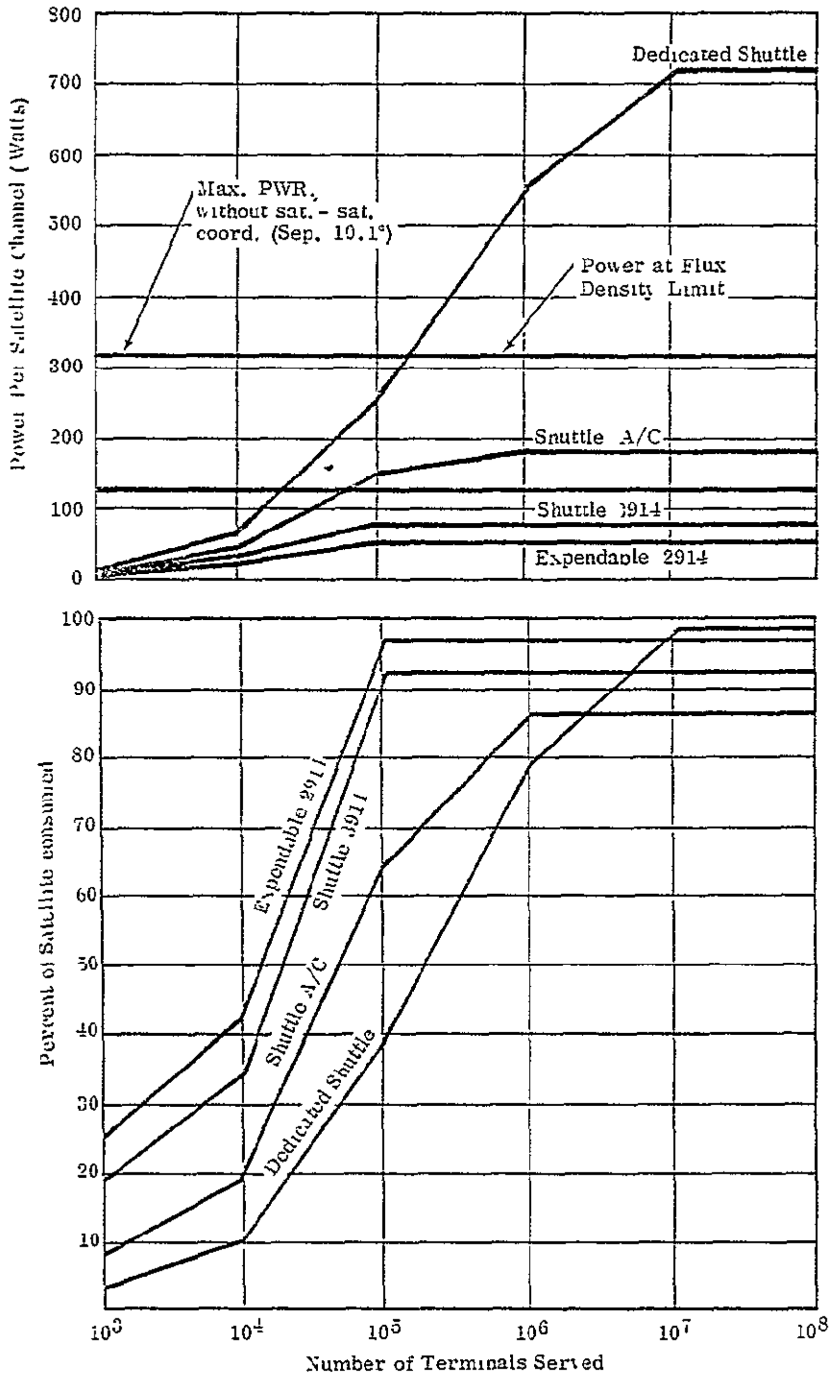

Figure 4-8 Satellite Power and Capacity Requirements
(4 Beam Ku-band Satellite 0.1% Link Outage) (TV Broadcast)

As indicated by Figure 4-8, the satellite power per channel increases rapidly as the network becomes larger. The system requires only four wideband signal accesses and corresponding satellite channels regardless of the network size. Consequently, the increase in terminals per satellite signal is directly proportional to the increase in network size. Consequently, satellite costs are spread over more terminals making rapid increases in satellite power cost-effective.

The indicated percentages of the satellite payload consumed reflect the high power requirements discussed above. At a network size of 10^4 terminals, the satellite capacity requirements are modest. However, for Ku-Band networks of 10^5 to 10^6 terminals only Shuttle Atlas-Centaur or Dedicated Shuttle sized satellites are adequate. When the upper bound on a satellite's power capability is reached the system can no longer be optimized as the number of terminals increases. Reasonable network sizes for this service are estimated to be on the order of 10^3 to 10^5 terminals in the period prior to 1985, consequently, a Shuttle Atlas-Centaur sized satellite is considered a reasonable selection.

The Ku-Band coordination limits displayed can be read directly from the four-beam satellite curve shown in Figure 3-5. Satellite output backoff is not a factor since there is only one signal per channel. Further, the satellite channel center to center bandwidth for this service is taken to be about 27 MHz, therefore, no adjustments have to be made to the curve in the figure. A second Ku-Band consideration is the flux density limitations on radiation into an adjacent administration's territory. This has not been a factor in other services since the limitations allow high satellite power levels. The requirement for broadcast service (see section 3.3.A.2.) states that the flux densities shall not exceed $-105 dBW/M^2$ for 99% of the worst month. The allowable power per satellite channel is then given by:

$$P_{SC}(dB) = -105-10 \log_{10}(1/4 \quad R^2) - G_s + L_s + M_{80} \qquad \text{——}$$

where:

- R, L_s and M_{B0} are as defined in Section 3.3.A.2
- G_s is the satellite antenna gain at the edge of coverage. It is about 34dB for a four-beam Ku-Band satellite.

With $M_{BO} = 0$ for this service, $P_{SC} = 316$ watts which is a factor only when a Dedicated Shuttle satellite is used with networks of more than 10^5 terminals.

The S-Band power at the flux density limit, shown in Appendix 7, is essentially the same as that derived for the "TV for Retransmission" service. An identical amount of spreading (i.e., W = 8.3 MHz) can be employed. In this case, the total satellite channel bandwidth becomes 30 MHz and the link losses due to spreading are 1.4dB. This compares with 40-MHz satellite channel bandwidth and 1dB of spreading losses for the "TV for Retransmission" service. With half of the link losses made up by increasing satellite power, the allowable power limit for this service is 0.2dB less (i.w, 20.1 watts rather than 21 watts).

3.0 Satellite and Ground Terminal Cost Vs. Network Size

The dramatic decrease in average annual cost per terminal as the network size increases is shown by Figure 4-9. In this case, there is some reduction in the rate of decrease at network sizes of 10^7 and 10^8 terminals, because satellite costs have become insignificant and the limitations on available satellite power have frozen the ground terminal antennas at the appropriate compatible size. The figure compares Ku-Band, S-Band, and UHF costs. The S-Band results do not take satellite flux density limitations into consideration. At UHF, there is at present no satellite freqeuncy allocations so there is no flux density limit to consider. Again, there is a considerable potential system cost advantage at the lower frequencies resulting from the lower cost of earth terminal technology.

Imposing the S-Band satellite flux density limitations does have a modest effect on the Ku-Band/S-Band cost trade-off comparison. When a 4-beam Atlas Centaur satellite is used, the S-Band limitations become a factor at a network size of about 10^4. The limits impose a 20-watt power per channel limitation on the satellite and freeze the S-Band ground terminal performance at a G/T of about 7.6dB/°K. The comparative Ku-Band/S-Band ground costs, when the S-Band limits are imposed, are summarized in Table 4-14. As shown, the S-Band costs are still significantly below the Ku-Band costs for network sizes to 10^6 terminals. At network sizes of 10^7 and 10^8 terminals, the costs of the two are about the same.

Table 4-14. Ku-Band/ S-Band Cost(1) Comparison with Flux Density Limits Imposed

Frequency	Flux Limits	Number of Terminals 10^3	10^4	10^5	10^6	10^7	10^8
Ku-Band(2)	No	\$6,500	\$2,000	\$700	\$320	\$175	\$145
S-Band(2)	Yes	4,750	983	420	253	160	160
	No	4,750	976	313	147	85	81

NOTES: (1) Average annual cost per user for the satellite and ground terminal.

(2) Four-beam Shuttle Atlas-Centaur sized satellite.

4.0 Ground Terminal Requirements

The variations in the Ku-Band ground terminal performance parameters, as a function of increases in the ground network size, are depicted in Figure 4-10. Similar results for the S-Band and UHF terminals are depicted in Appendix 7. The expected decreases in G/T with increased network size as shown by the figure are accomplished primarily with the antenna.

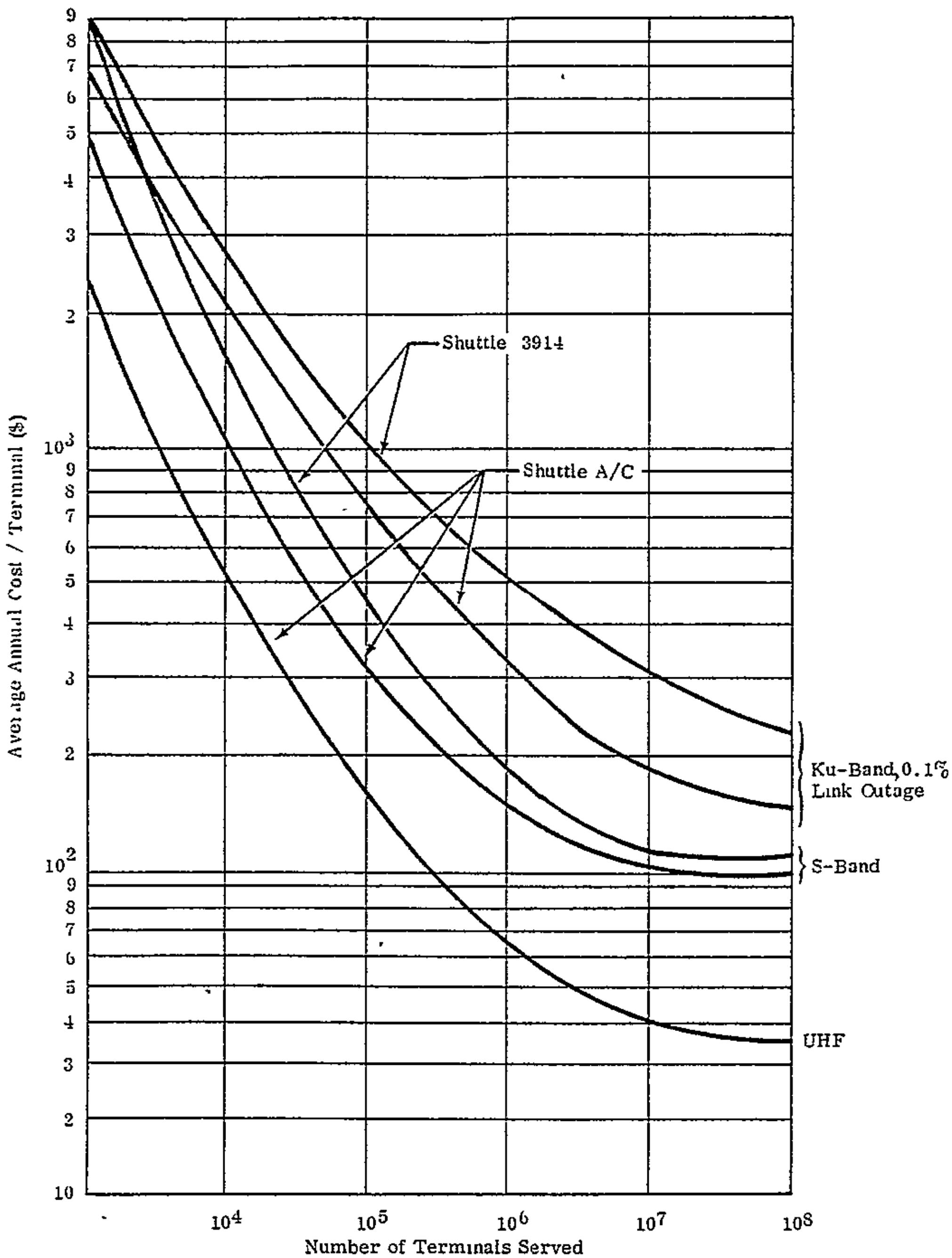

Figure 4-9 Annual Cost Vs. Network Size and Frequency Band (4 Beam Satellite) (TV Broadcast)

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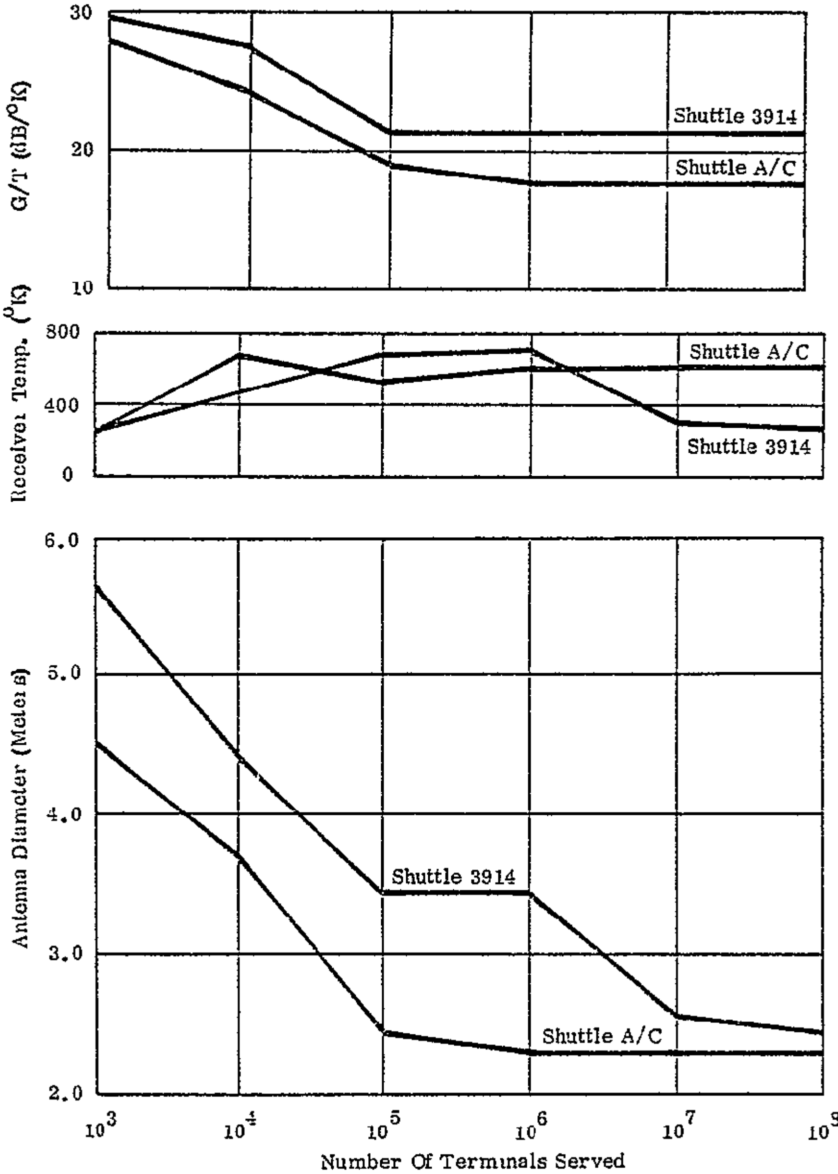


Figure 4-10. Ground Terminal Requirements
(S-Band; 4 Beam Satellite) (TV Broadcast)

Flattening of the G/T trend at network sizes of 10^5 and 10^6 terminals is due to the power limitations of particular satellites. The displayed receive system temperature curves are somewhat surprising in that they normally are expected to increase as the G/T decreases and hold constant when the G/T is constant. There are two reversals to that trend. The first occurs between network sizes of 10^4 and 10^5 terminals when a Shuttle Atlas-Centaur satellite is used. This is due to transitioning through one of the break points in the Ku-Band antenna cost and performance curves, (see the transition from the 12-foot antenna to the 7.5-foot antenna to the 7.5-foot antenna in Appendix 1.) The second occurs between network sizes of 10^6 and 10^8 terminals when a Shuttle 3914 satellite is used. This reflects a faster rate of cost decrease for receiver technology than for antenna technology as the size of the buy increases. Notice that this tradeoff effect is not general and does not occur for all matchings of antennas and receivers. The figure shows that for a network of 10^4 terminals operating with a Shuttle Atlas-Centaur satellite, a 3.7 meter (i.e., 12-foot) manually steered Cassegrain antenna and a 650°K GaAs FET receiver is optimum. Typical variations in G/T that produce no more than a 10% increase in system cost are displayed in Table 4-15. The bounding parameters are read from the system optimization curves shown in Appendix 7. The table does not display the bounding parameters for the Shuttle Atlas Centaur satellite with a network of 10^4 terminals. However, the computer data base shows that the lower bound G/T is 2dB less than optimum (i.e., at 21.3dB). This corresponds to a 3-meter (i.e., 10-foot) manually steered Cassegrain antenna with a 650°K GaAs FET receiver. If requirements are further reduced by eliminating the extra satellite antenna gain to the Southeast, a G/T of about 19dB results. This corresponds to an 8.5 foot manually steered Cassegrain antenna and a 700°K GaAs FET receiver.

Table 4-15 shows that the S-Band antenna sizes are smaller than corresponding Ku-Band sizes while the receiver requirements are more stringent. The same is true at UHF, (see 10^4 terminals.) Again, this occurs because receiver technology at the lower frequencies is considerably less expensive while the antennas are only moderately less expensive. The deviations from this pattern at 10^6 terminals occur because the low frequency satellites do have sufficient power to allow system optimization to occur while the Ku-Band Atlas-Centaur did not (see Figure 4-8). With a 4-beam S-Band, Shuttle Atlas-Centaur satellite operating with a network of 10^4 terminals and with the flux density limits imposed, the terminal parameters are: (G/T = 7.6dB/°K, antenna diameter = 2.4 meters (i.e., an 8-foot fixed pointed prime focus fed parabolic reflector), and receiver temperature =275°K (i.e., a GaAs FET low noise amplifier).

5.0 Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items, are summarized in Table 4-16. Annual costs for a Ku-Band network of 10^4 terminals using a Shuttle Atlas-Centaur sized satellite are about $2,100. This amounts to about $175 per month or less than $2 per student per month if only 100 pupils are served in an educational TV system. The corresponding costs at S-Band are even less (i.e., about $95 per month or less than $1 per 100 students per month). The fixed item costs are entirely equipment costs. These costs are broken out in detail in Appendix 1.

Table 4-15. Bounds on Ground Terminal Receiver Temperature and Antenna Diameter (TV Broadcast)

LAUNCH VEHICLE	No. Term.	Frequency	Lower G/T Bound			Upper G/T Bound		
			G/T	Rec. Temp.	Ant. Dia.	G/T	Rec. Temp.	Ant. Dia.
Shuttle 3914	10^4	Ku - Band .1%	23.5 db.	580 (°K)	3.5 (meters)	28.5 db.	265 (°K)	4.5 (meters)
		S Band	6.0 db.	275 (°K)	2.0 (meters)	10.5 db.	160 (°K)	2.5 (meters)
		UHF (1)	-6.5 db	460 (°K)	2.0 (meters)	-4.0 db	275 (°K)	3.0 (meters)
Shuttle A/C	10^6	Ku-Band .1%	18.0 (2) db	580 (°K) (2)	2.5 (2) (meters)	19.0 db	450 (°K)	2.5 (meters)
		S Band	-3.5 (2) db	1220 (°K) (2)	1.5 (2) (meters)	0 5 db.	1220 (°K)	2.0 (meters)
		UHF	-16.0 db.	2200 (°K)	1.5 (meters)	-10.0 db.	590 (°K)	1.5 (meters)

Notes: (1) Shuttle AC only considered for UHF at 10^4

(2) Represents lowest cost point on curve that didn't optimize

Table 4-16. Breakdown of Total Average Annual Cost/Terminal
(TV Broadcast)

Launch Vehicle	Number Terminals	Frequency	Total ($) Annual Cost	Percent of Cost in		
				Satellite	Ground Terminal	Fixed
Shuttle 3914	10^4	Ku - Band .1%	2675	35	63	2
		S - Band	1500	61	37	3
		UHF (1)	645	47	43	10
		Ku - Band .1%	345	10	82	8
Shuttle A/C	10^6	S - Band	175	15	70	15
		UHF	105	15	57	28

Note: (1) Shuttle A/C only considered for UHF at 10^4

The table shows that ground terminal costs are dominant in almost all cases with satellite costs important only for modest sized networks (i.e., 10^4 terminals or less). This distribution of costs is further verified in the sensitivity analysis. Results of this analysis are displayed in Appendix 7. The analysis considers independent $\pm$ 10dB variations in link performance, satellite cost, and ground terminal cost with all other factors constant. Table 4-16 also shows that fixed equipment costs are not an important factor in this service. This all points to concentrating on the ground terminals in attempts to reduce costs. Obviously, low frequency operation even when flux density limits are considered is a promising approach. Satellite improvements are of benefit on modest sized networks (i.e., 10^4 terminals or less). Big satellites give considerable cost advantage provided the excess capacity can be sold. Wider satellite channel bandwidths might be advantageous on S-Band satellites in particular. S-Band operation with a one-beam satellite is also a consideration for small networks. Longer life and higher reliability satellites, shuttle optimized satellites, higher efficiency solar arrays, ion jets, etc. are all of potential benefit.

C. FM VOICE/MUSIC FOR RETRANSMISSION

1. Average Annual Cost Versus Satellite Channel Bandwidth

Since this is a narrow band service, multiple narrow satellite channel bandwidths are considered. As in the transmit/receive system optimizations, variable channel bandwidths are used as a means for varying the allocation of satellite power per channel and cost per channel. This is accomplished by varying the number of signals accessing a satellite channel thereby shifting the system optimization point along the satellite transponder power-cost curve. In the case of the transmit/receive services, such shifts are used to optimize the satellite power per channel and thereby realize a more cost-effective satellite design. Similar shifts also can be expected to be of benefit in the receive only services when the network size is small. However, when the network size is large, satellite power requirements become large anyway as is shown for the two previous receive only services. In such cases, it is necessary to reduce satellite channel bandwidth and channel power so that the system optimization point shifts downward to a satellite power which is realizable for the particular satellite. Notice that these shifts to narrower satellite channel bandwidths are not necessarily real design changes, in fact, it is possible to use 36 MHz channels with all of the power allocated to a narrow band signal accessing that channel.

The results of the bandwidth variations carried out on a Ku-band system are depicted in Table 4-17. Similar results for an S-band system are described in Appendix 7. As shown, the bandwidth variations considered do, in most cases, carry the satellite and ground complex costs through an optimum. At bandwidths less than optimum, inefficient low-powered satellite transponders result due to excessive filter weight. At bandwidths greater than optimum, the satellite transponder power is being divided between too many user signals so that an optimization cannot occur between the satellite and ground complex. Notice that the optimum bandwidths become narrower

Table 4-17. Average Annual Cost Vs. Bandwidth (Ku-band, 1 & 4 Beam Satellite, 0.1% Link Outage) (Radio Distribution)

Launch Vehicle	BSC* MHz	1 Beam 10^2	1 Beam 10^4	4 Beams 10^2	4 Beams 10^4
Shuttle 3914	1.92	$ 9,115	$ 1,725	$ 7,515	$ 1,090
	7.68	6,905	1,725	4,470	1,120
	15.36	6,720	1,680	4,145	1,345
	30.72	6,760	1,795	4,730	1,820
Shuttle A/C	1.92	7,135	1,415	5,175	885
	7.68	5,825	1,330	3,505	885
	15.36	5,690	1,290	3,365	930
	30.72	5,675	1,310	3,355	1,160

* Satellite Transponder Bandwidth

as the size of the ground network increases and the size of the satellite decreases. These represent (for the satellite) "power-starved" cases. The result is a complex set of applicable bandwidth selections. Those made and used in subsequent evaluations of this service are depicted in Table 4-18. The choices for the Shuttle 3914 satellites are based on operation with a network of 10^2 terminals. The Shuttle Atlas Centaur satellite choices assume operation with a network of 10^4 terminals.

Table 4-18. Bandwidth Selections for FM Voice/ Music for Retransmission

Frequency Band	No. Terminals	Launch Vehicle	1 Beam Satellite	4 Beam Satellite
Ku-Band	10^2	Shuttle 3914	15.36MHz	15.36MHz
	10^4	Shuttle A/ C	7.68MHz	7.68MHz
S-Band	10^2	Shuttle 3914	30.76MHz	30.76MHz
	10^4	Shuttle A/ C	15.36MHz	15.36MHz

2. Average Annual Cost Vs. Number Beams per Satellite

The system cost comparisons between one and four beam Ku-band satellite designs are displayed in Table 4-19. Similar cost comparisons for an S-band satellite are given in Appendix 7. The comparisons are similar to those for the "TV Direct to the User" service. The four-beam satellite Ku-band system costs are significantly less regardless of the size of the satellite or network. The four-beam S-band costs are less for a network of 10 terminals only when an Atlas-Centaur or larger satellite is used. At a network size of 10^5 terminals, the four-beam S-band costs are less for Delta 3914 or larger satellites. Such agreement with the four-beam system advantages observed for the "TV Direct to the User" service are somewhat surprising. The four-beam approach has generally been shown to be comparatively poorer when the system optimization occurs at low satellite power levels. This is a service where threshold extension FM allows operation at link C/N ratios of only 8 dB, the satellite channel bandwidths are, in general, less than 22 MHz, and the number of terminals/satellite signal are smaller. However, satellite output power backoff is required, redundant ground terminals are used, and the satellite channel costs are divided among a large number of signals accessing the channel. Compensating effects occur and reasonably high satellite channel power results even at small network sizes. Consequently, the four-beam approach is once again selected as an example for all further Ku-band and S-band system configurations.

Table 4-19. Average Annual Cost/Terminal vs. Number of Beams/Satellite (Ku-Band Satellite) (Radio Distribution)

	Launch Vehicle	10 Term.		10^5 Term. (2)	
		0.1% Outage	0.05% Outage	0.1% Outage	0.05% Outage
1 Beam	Exp. 2914	$ 11,060 (1)	$ 12,380 (1)	$ 880	$ 1,100
1 Beam	Exp 3914	10,315 (1)	11,560 (1)	815	995
1 Beam	Shuttled 3914	9,535 (1)	10,715 (1)	750	915
1 Beam	Exp A/C	8,840 (3)	10,440 (3)	665	790
1 Beam	Shuttle A/C	8,495 (3)	9,475 (3)	610	700
1 Beam	Shuttle Ded.	7,030 (3)	7,945 (3)	520	570
4 Beams	Exp 2914	7,535 (1)	8,515 (1)	575	640
4 Beams	Exp 3914	6,540 (1)	7,495 (1)	515	575
4 Beams	Shuttle 3914	5,865 (1)	6,820 (1)	480	535
4 Beams	Exp A/C	5,920 (3)	6,600 (3)	425	450
4 Beams	Shuttle A/C	5,285 (3)	5,890 (3)	400	415
4 Beams	Shuttle Ded.	4,225 (3)	4,765 (3)	365	360
4 Beams					

Notes: (1) Employs 15.36 MHz Bandwidth
(2) Employs 1.92 MHz Bandwidth
(3) Employs 7.68 MHz Bandwidth

3. Satellite Requirements

The Ku-band satellite power per channel as a function of the number of terminals in the network is depicted in Figure 4-11. Similar curves are displayed for the S-band satellites in Appendix 7. The same basic trend in power per channel observed in the previous receive only services (See Section 4.3.A and 4.3.B) are illustrated in Figure 4-11. The Expendable 2914 and Shuttle 3914 satellites reach their maximum power per channel capability at a network size of 10^3 terminals. The power capabilities of these satellites are "magnified" relative to those of the Dedicated Shuttle and Shuttle Atlas Centaur satellites by the use of wide channel bandwidths (i.e., 15.36 MHz rather than 7.68 MHz).

This service is similar to the "TV for Retransmission" service because the required number of satellite signal slots is expected to increase as the network size increases. The assumed requirements are for 1, 4, 8, 16 and 32 signal slots at network sizes of 10, 10^2, 10^3, 10^4, and 10^5 terminals, respectively. When these satellite access requirements are combined with a capability to handle 32 signals in a 7.68 MHz satellite channel and 64 signals in 15.36 MHz channel, the composite satellite channel requirements become as indicated in the figure. These are 0.03, 0.125, 0.25, 0.5 and 1 channels in Shuttle Atlas Centaur or larger satellites and 0.016, 0.063, 0.125, 0.25 and 0.5 channels in Shuttle 3914 or smaller satellites at network sizes of 10, 10^2, 10^3, 10^4, and 10^5 terminals, respectively.*

The required satellite payload capacity, shown in Figure 4-11, is quite modest as might be expected with the modest channel requirements indicated above. If the maximum requirement is for one channel, then the maximum consumption can be only 25% of a satellite having a minimum of four channels. The indicated payload requirement follows the normal trend up to a network size of 10^3 terminals. At this point, the rate of increases falls for Shuttle 3914 and smaller satellites since the maximum power per channel is attained. From this point on only the number of channels required increases, which in turn increases the satellite payload "consumption". A reasonable sized network for this service, in the time period prior to 1985, is of the order of 10^2 to 10^4 terminals. Either a Shuttle Atlas Centaur or a Shuttle 3914 satellite is sufficient at a network size of 10^2 to 10^3 terminals. However, at 10^4 terminals the Shuttle Atlas Centaur is the clear choice due to channel power limitations.

The Ku-band coordination limits, shown in the figure, are based on the four-beam satellite curve shown in Figure 3-5. However, the limit has to be adjusted to account for satellite output backoff and a channel bandwidth of less than 27 MHz. Channel center to channel center spacings of 20 MHz and 10 MHz will be adopted. Accordingly, for the small satellites:

$$P_{coord} = P_{curve} + 5.1 + 10 \log_{10} (20/27) \quad \text{or}$$

$$P_{coord} = P_{curve} + 3.8\text{dB}$$

* It is assumed that the remainder of the satellite channel is available for another service.

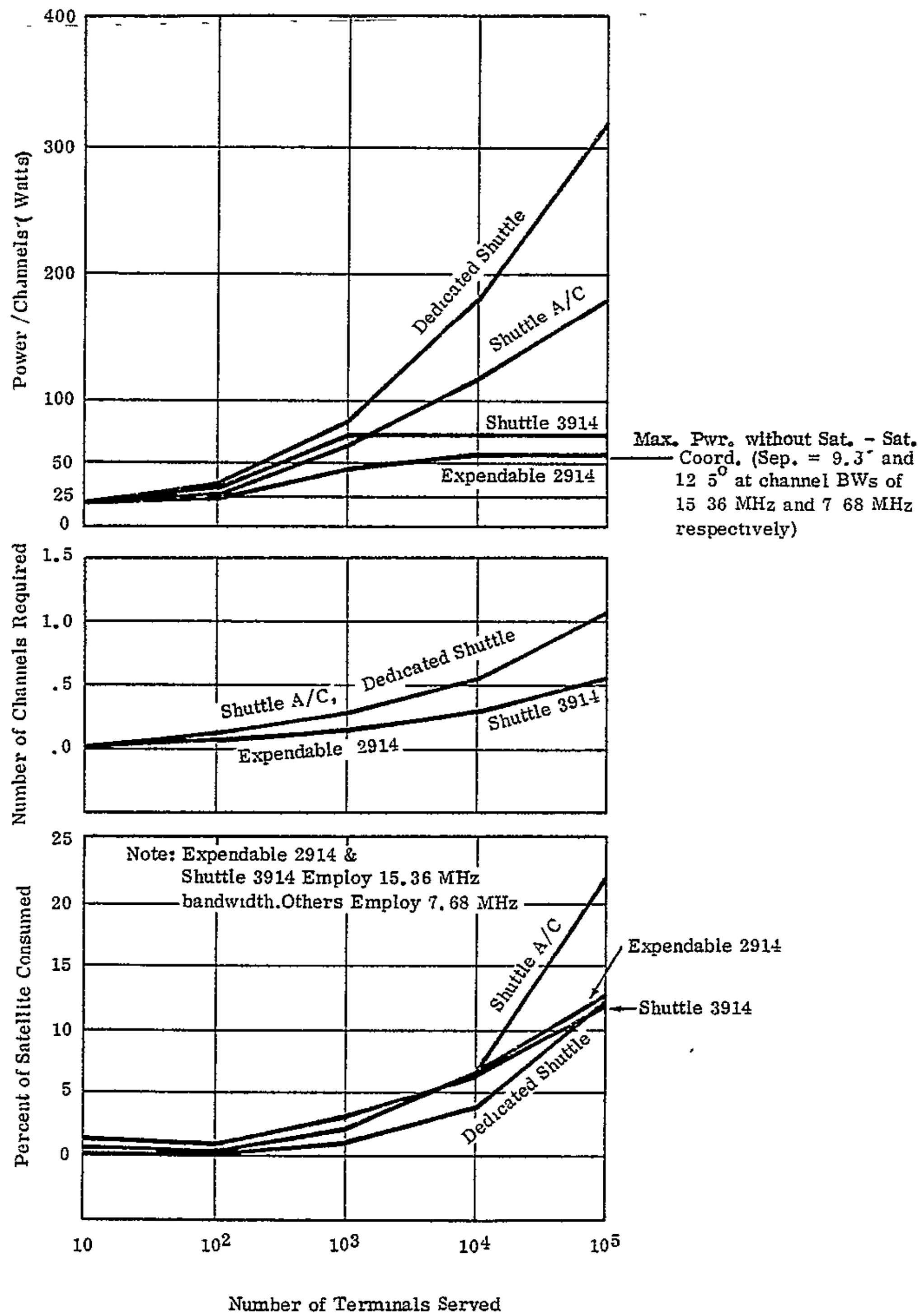


Figure 4-11 Satellite Power and Capacity Requirements
(Ku-band, 4 Beam, 0.1% Link Outage (Radio Distribution)

and for the large satellites:

$$P_{coord} = P_{curve} + 5.1 + 10 \log_{10} (10/27) \quad \text{or}$$

$$P_{coord} = P_{curve} + 0.8\text{dB}$$

The S-band power at the flux density limit, shown in Appendix 7, is determined from the basic equation developed in Section 4.3.A.2. For this service it is:

$$P_{SC}(\text{dB}) = -20 + 10 \log_{10} \frac{W}{4}, \; -5 \log_{10} \frac{200+W}{200} + M_{BO} - 10 \log_{10} \frac{B_{SC}}{B5}$$

where:

- 200KHz is the signal bandwidth
- the satellite portion of the spreading loss (i.e., $5 \log_{10} \frac{200+W}{200}$ is 0.65dB and the spreading W is 70 KHz.
- $M_{BO} = 5.1$dB
- $B_S = 0.24$MHz is the center to center signal separation in the satellite
- $B_{SC} = 30.72$MHz for Shuttle 3914 or smaller satellites and
  = 15.36MHz for Shuttle A/C or larger satellites

Accordingly:

P_{SC} = 60 watts for small satellites and

P_{SC} = 30 watts for large satellites

4. Satellite/Ground Terminal Cost Vs. Network Size

The same cost trends as a function of network size, observed for the previous receive only services also pertain to this service, as indicated by Figure 4-12. The divergence in the Shuttle 3914 and Shuttle A/C rate of cost decreases, at network sizes of 10^4 and 10^5 terminals, occur because of the output power limitations of the smaller satellites. These constraints are such that a satellite-ground complex optimization cannot take place. The S-band results do not take satellite flux density limitations into consideration. As shown, there is considerable potential cost advantage at the lower frequencies.

Imposing the S-band flux density limitation does not significantly change the Ku-band/S-band cost trade-off results. The comparative Ku-band and S-band costs, with and without the flux density limits imposed, are summarized in Table 4-20 based on the use of a four-beam Shuttle Atlas Centaur satellite. The flux density limits impose a 30-watt power per channel constraint on the satellite and freeze the S-band ground terminal performance at a G/T of about 4.5 dB. As indicated by the table, the flux density limits are not a factor until a network size of 10^3 terminals is reached and the S-band costs remain well below the Ku-band costs out to a network size of 10^4 terminals. At 10^5 terminals, the cost of the two approaches is about the same.

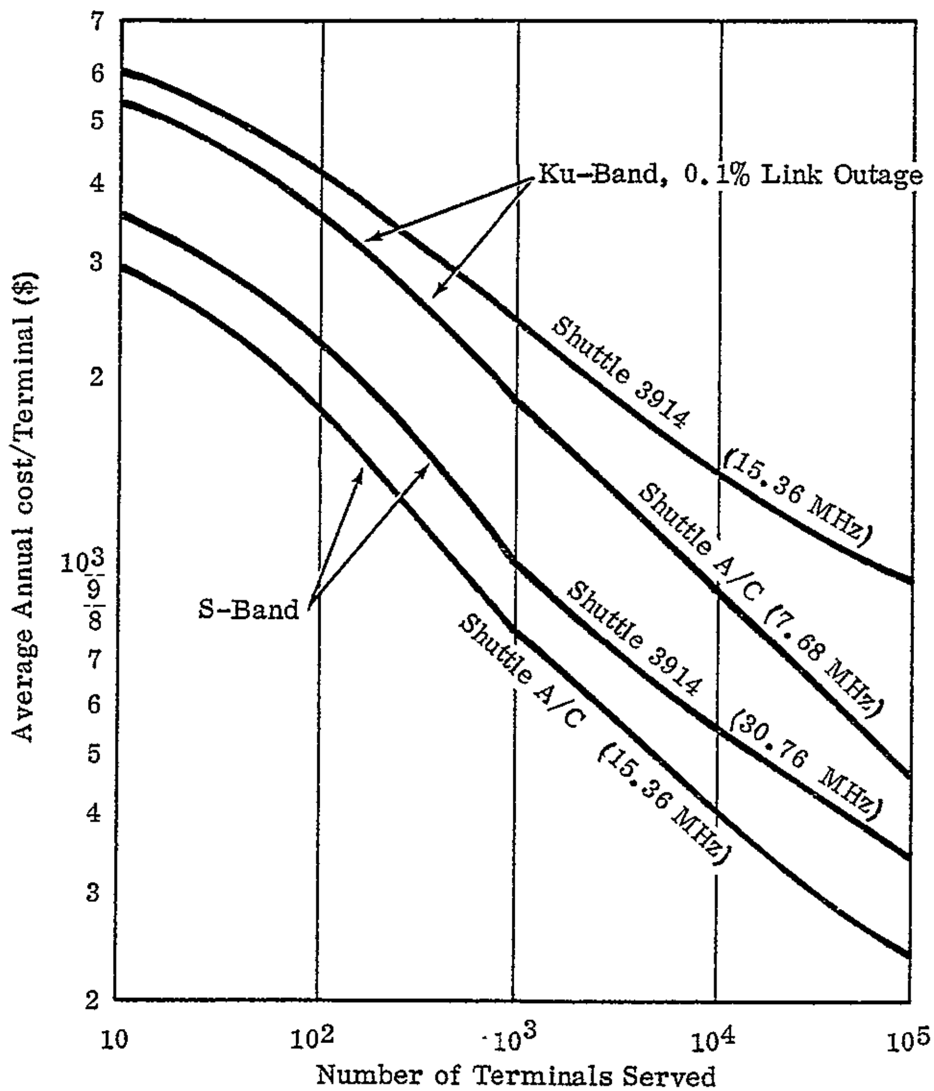


Figure 4-12. Average Annual Cost/Terminal Vs. Network Size and Frequency Band (4 Beam Satellite)

Table 4-20. Ku-Band/ S-Band Cost(1) Comparison with Flux Density Limits Imposed (Radio Distribution)

Frequency	Flux Limits	Number of Terminals				
		10	10^2	10^3	10^4	10^5
Ku-Band(2)	No	$5,300	$3,500	$1,750	$880	$430
S-Band(2)	Yes	$2,900	$1,800	$865	$610	$400
	No	$2,900	$1,800	$770	$420	$220

Notes: (1) Costs are average annual cost/ user for the satellite & ground terminal

(2) A four-beam Shuttle Atlas-Centaur sized satellite is used.

5.0 Ground Terminal Requirements

Variations in Ku-Band ground terminal performance parameters as a function of increases in ground network size are depicted in Figure 4-13. Similar results for the S-Band terminals are given in Appendix 7. The displayed G/T trends run counter to the corresponding satellite power per channel requirements (see Figure 4-11) as expected. This includes a flattening of the ground terminal curve for a Shuttle 3914 satellite at network sizes larger than 10^3 terminals, due to the satellite power limit. Decreases in G/T are accomplished by both smaller antennas and higher noise temperature receivers. However, the rate that antenna size decrease appears to level off at an antenna diameter of about 2.3 meters (i.e., $\approx$ 7 feet), (see the Shuttle A/C antenna curve.) This is a size just below one of the break points in the Ku-Band antenna cost versus diameter curves (see Appendix 1) and reflects the change to a fixed pointed prime focus fed antennas with unpressurized feed. The resultant step in cost results in an antenna size that is optimum over a considerable range of G/Ts. The modest variations in the antenna and receiver pairings when G/T is constant (see the Shuttle 3914 antenna and receiver curves) are a result of changes in the slope of the component performance cost curves as the size of the buy increases.

The figure shows that for a network of 10^4 terminals operating with a Shuttle Atlas-Centaur satellite, a 2.3 meter (i.e., 7.5 foot) fixed pointed prime focus fed antenna and a 1200°K diode mixer receiver is optimum. Typical variations in G/T that produce no more than a 10% increase in system costs are displayed in Table 4-21. The bounding parameters are read from the system optimization curves shown in Appendix 7. The indicated lower bound G/T, when a Ku-Band Shuttle Atlas Centaur satellite operates with 10^4 terminals, is about 2dB below the optimum. This corresponds to a 2.3 meter antenna and a 1950°K diode mixer receiver. If the extra satellite antenna gain to the Southeast is eliminated, the resultant earth terminal G/T is only about 10.5dB, corresponding to a 1.8 meter (i.e., 6 foot) fixed pointed prime focus fed antenna and a 2190°K diode mixer receiver.

The table once again shows that S-Band antenna diameters tend to be lower than those required at Ku-Band due to the availability of inexpensive high performance receivers. Notice that the terminal G/T requirements are also comparatively less due to lower link margins. When a four-beam, S-Band, Shuttle Atlas Centaur satellite operates with 10^4 terminals and the flux density limits are imposed, the terminal parameters are: G/T = 4.5dB/$^\circ$K, antenna diameter = 2.3 meters (i.e., a 7.5 foot fixed pointed prime focus fed parabolic reflector) and receiver temperature = 660°K (i.e., a GaAs FET low noise receiver). These compare favorably with the Ku-Band parameters even though the G/T requirements have been inflated somewhat by the flux density constraints.

6.0 Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items are summarized in Table 4-22. Annual costs, for a four-beam Ku-Band Shuttle Atlas Centaur satellite serving a network of 10^4 terminals, is about $1,400, or about $115 per month. If each distribution terminal serves a few thousand users, the average cost per

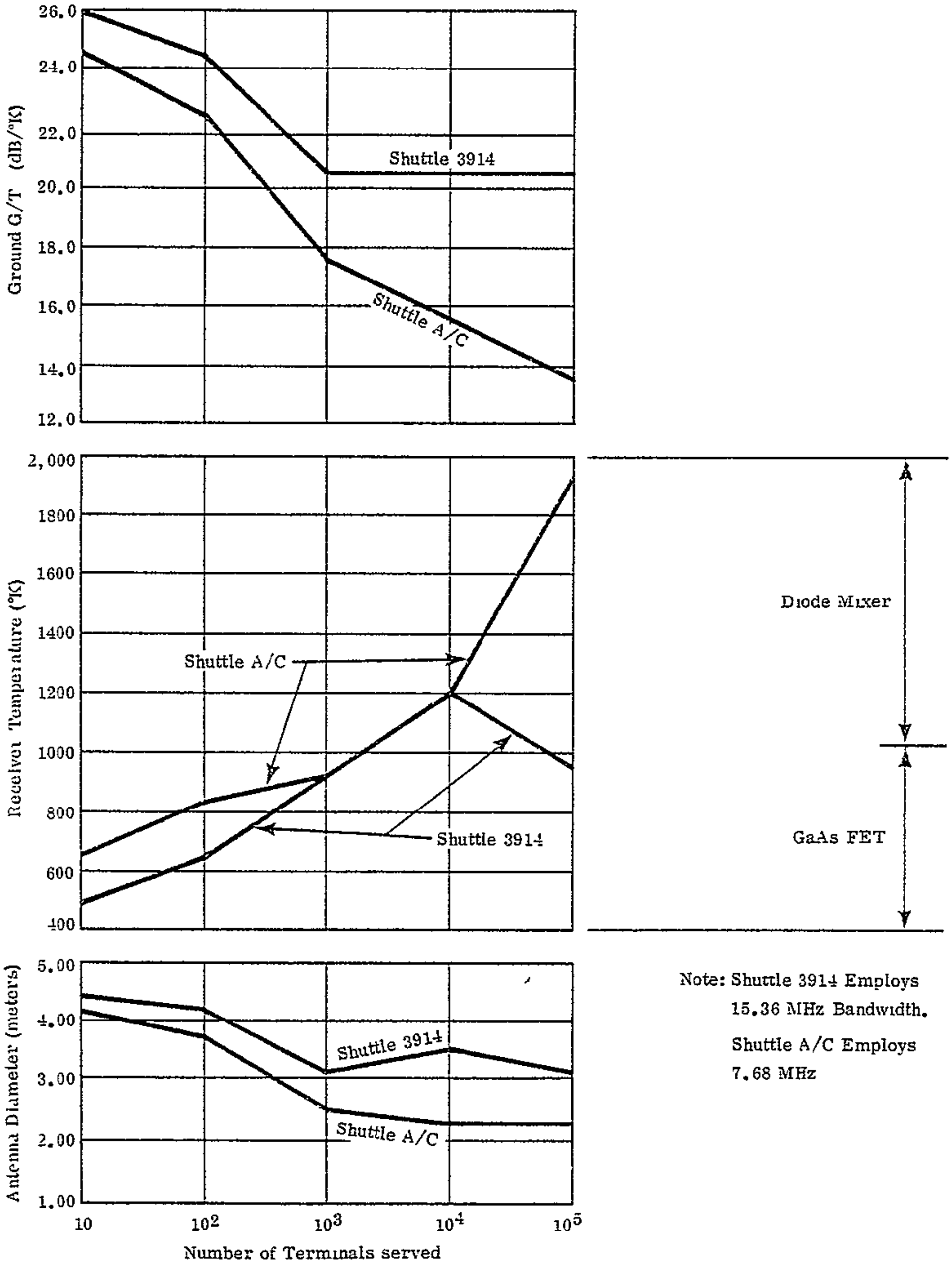


Figure 4-13 Ground Terminal Requirements
(Ku-Band, 4 Beam, .1% Link Outage) (Radio Distribution)

Table 4-21. Bounds on Ground Terminal G/T, Receiver Temperature, and Antenna Diameter (4 Beam Satellite) (Radio Distribution)

Frequency	Launch Vehicle	Parameter	Lower Bound	Upper Bound
Ku-band (1)	Shuttle 3914 (2)	G/T (dB/°K)	22.0	27.0
		Receiver Temp(°K)	950	350
		Ant. Dia. (meters	4.0	4.5
	Shuttle A/C (2)	G/T (dB/°K)	13.0	17.5
		Receiver Temp(°K)	1950	700
		Ant. Dia. (meters	2.5	2.5
S-Band (1)	Shuttle 3914 (3)	G/T (dB/°K)	4.5	9.5
		Receiver Temp(°K)	750	275
		Ant. Dia. (meters)	4.6	2.5
	Shuttle A/C (3)	G/T (dB/°K)	-4.5	0.5
		Receiver Temp(°K)	1950	1200
		Ant. Dia. (meters	1.5	2.0

Notes:

1) Shuttle 3914 assumes 10^2 terminals, Shuttle A/C assumes 10^4 terminals.

2) Shuttle 3914 assumes 15.36 MHz bandwidth, Shuttle A/C assumes 7.68 MHz, both launchers assume 0.1% link outage.

3) Shuttle 3914 assumes 30.76 MHz bandwidth, Shuttle A/C assumes 15.36 MHz.

Table 4-22. Breakdown of Total Average Annual Cost/Terminal (4 Beam Satellite) (Radio Distribution)

Frequency	Launch Vehicle	Total Ave. Annual Costs ($)	Percent of Cost In:		
			Satellite	Gnd Terminal	Fixed
Ku-band (1)	Shuttle 3914 (2)	5,445	27	49	24
	Shuttle A/C (2)	1,390	18	46	36
S-Band (1)	Shuttle 3914 (3)	3,520	31	32	37
	Shuttle A/C (3)	930	9	36	55

(1) Shuttle 3914 Assumes 10^2 terminals, shuttle A/C assumes 10^4 terminals

(2) Shuttle 3914 assumes 15.36 MHz bandwidth shuttle A/C assumes 7.68 MHz. Both launches assume .1% link outage.

(3) Shuttle 3914 assumes 30.76 MHz bandwidth, shuttle A/C assumes 15.36 MHz.

user per month becomes pennies. The corresponding S-Band costs are even less (i.e., \$930 annually without considering the flux density limits and \$1100 annually when the limits are imposed). The fixed item costs are entirely equipment costs, which are broken out in detail in Appendix 1.

The table shows that ground terminal costs are, generally, the dominating element in the system costs. This is similar to the situation in the "TV Direct to the User" service. The distribution of costs between the satellite and ground terminals is further verified in the sensitivity analysis. Results of this analysis are displayed in Appendix 7. The analysis considers independent $\pm$ 10dB variations in link performance, satellite cost and ground terminal cost with all other factors constant. Table 4-22 also shows that fixed equipment costs can be significant, particularly at the larger network sizes. These are primarily the costs of a threshold extension demodulator interfacing at IF. The cost of this technology does not drop rapidly as buy sizes increase. The best hope of reducing costs appears to lie in operating at lower frequencies and encouraging the deployment of large networks. Employing big satellites (e.g., Shuttle Atlas-Centaur) is also of some benefit. Other improvements in satellite design are likely to have little impact.

D. COMPRESSED BANDWIDTH TV

1. Average Annual Cost Versus Satellite Channel Bandwidth

The satellite channel bandwidth variation, and cost implications for a Ku-Band system are summarized in Table 4-23. Similar results, for S-Band systems, are given in Appendix 7. In this service, the impact of eliminating the satellite output power backoff is considered once again. The signal is identical to that of the Compressed Bandwidth TV/Facsimile service, discussed in Section 3.3.B. Accordingly, the satellite channel bandwidth variations also are identical. That is, they encompass the one, and three signal per satellite channel cases. The results, displayed in the table, are quite similar to those for the "FM Voice/Music for Retransmission" service, discussed in Section 4.3.C, (where eliminating the backoff is not a consideration). The implication is that once again the optimization point on the satellite channel power and cost curves has a greater impact on satellite and terminal costs than the backoff. This is in general agreement with the results for the transmit/receive services (see Sections 3.3.B and 3.3.E).

Table 4-23 shows that, for a Ku-Band network of 10^4 terminals, the bandwidth variation carries the satellite and terminal costs through an optimum. For networks of 10^2 terminals, the maximum bandwidth results in the lowest cost and appears to be nearly optimum since the cost decrease in going from a 24 MHz to a 36 MHz bandwidth is small. Based on these results, and the S-Band results summarized in Appendix 7, the bandwidth selections applied to all subsequent evaluations of this service are as depicted in Table 4-24. The choices for the Shuttle 3914 satellites reflect a system configured to provide service to 10^2 terminals. The choices, for the Shuttle Atlas Centaur satellites, assume service is supplied to 10^4 terminals. The narrower bandwidth selections represent the satellite "power starved" cases. The S-Band Shuttle 3914 choices are at the maximum bandwidth available, however, this is the one instance in this service where it appears that wider bandwidths may be of some benefit. The rate of cost decrease remains huge at this bandwidth (see Appendix 7).

Table 4-23. Average Annual Cost/Terminal Vs. Bandwidth (Kuband Satellite, 0.1% Link Outage) (Compressed TV Distribution)

Launch Vehicle	B_{SC}* MHz	1 Beam		4 Beams	
		10^2	10^4	10^2	10^4
Shuttle 3914	12	34,540	2,975	36,725	2,330
	24	22,170	2,660	21,475	1,840
	36	20,085	3,275	17,375	2,030
Shuttle A/C	12	23,885	2,270	22,420	1,570
	24	15,945	2,245	13,440	1,320
	36	15,510	2,745	11,600	1,600

*Satellite transponder Bandwidth

Table 4-24. Bandwidth Selections for Compressed Bandwidth TV

Frequency Band	No. Terminals	Launch Vehicle	1-Beam Satellite	4-Beam Satellite
Ku-Band	10^2	Shuttle 3914	36MHz	36MHz
	10^4	Shuttle A/ C	12MHz	24MHz
S-Band	10^2	Shuttle 3914	36MHz	36MHz
	10^4	Shuttle A/ C	24MHz	36MHz

2.0 Average Annual Cost Vs. Number of Beams Per Satellite

The system cost comparisons between one and four-beam Ku-Band satellites are given in Table 4-25. Similar cost comparisons for an S-Band satellite are given in Appendix 7. The comparisons are sim lar to those observed for the three previous receive only services. The four-beam system advantage does not become significant unless the size of the satellite or the ground complex is sufficiently large so that large satellite output powers channel (e.g., 720 watts) are required. Further, the four beam advantage is less and occurs at even larger satellites and network sizes when S-Band is considered. At S-Band with 10 terminals in the network, there is no advantage to four beams until a Shuttle Atlas-Centaur sized satellite is considred. With 10^5 terminals in the network, the break even point occurs at Delta 3914 sized satellites and all larger satellites provide an advantage. Once again, the one-beam S-Band system is never at a serious cost disadvantage relative to the four-beam system, (see Section 4.3.A.1 for reasons). However, based on the Ku-Band results, the four-beam approach is selected for further consideration in all cases.

3.0 Satellite Requirements

The Ku-Band satellite power per channel as a function of the number of terminals in the network is depicted in Figure 4-14. Similar requirements for the S-Band satellites are given in Appendix 7. As in previous receive only services, the power per channel increases as the network and satellite size increases, (see Section 4.3.A.2 for reasons). However, the trend as a function of Ku-Band satellite size, is broken by the wider bandwidths selected for use on the Expendable 2914 and Shuttle 3914 satellites. This selection results in satellite channel powers that overlap those of the Shuttle Atlas-Centaur and Dedicated Shuttle satellites. The trend, as a function of S-Band satellite size, is broken by the abrupt "flattening" of the Expendable 2914 satellite cost per channel versus power per channel curves at an 11-watt power level, (see Section 3.7), which results in no significant cost improvements at lower channel powers; therefore, lower powers are never selected.

The power per channel requirements are, in general, somewhat lower for this service than for previous TV services. The C/N requirements are low due to digital operation and the use of error correcting coding. The number of terminals per satellite

Table 4-25. Average Annual Cost/Terminal Vs. Number of Beams/Satellite, Ku-band Satellite) (Compressed TV Distribution)

		10 Term.		10^5 Term.	
	Launch Vehicle	0.1% Outage	0.05% Outage	0.1% Outage	0.05% Outage
1 Beam	Exp 2914 (1)	$ 51,351	$ 55,188	$ 1,801	$ 2,500
	Exp 3914 (1)	44,558	48,385	1,694	2,311
	Shuttle 3914 (1)	37,745	41,530	1,581	2,128
	Exp A/C (2)	64,576	67,797	934	1,350
	Shuttle A/C (2)	53,088	55,7-9	837	1,218
	Ded. Shuttle (2)	36,523	38,580	689	1,000
4 Beams	Exp 2914 (1)	55,528	58,069	1,099	1,507
	Exp 3914 (1)	43,975	46,920	989	1,331
	Shuttle 3914 (1)	36,495	38,962	906	1,235
	Exp A/C (3)	35,478	37,290	564	807
	Shuttle A/C (3)	29,034	30,846	513	732
	Ded. Shuttle (3)	19,578	21,213	430	593

Notes:
(1) Employs 36 MHz Bandwidth
(2) Employs 12 MHz Bandwidth
(3) Employs 24 MHz Bandwidth

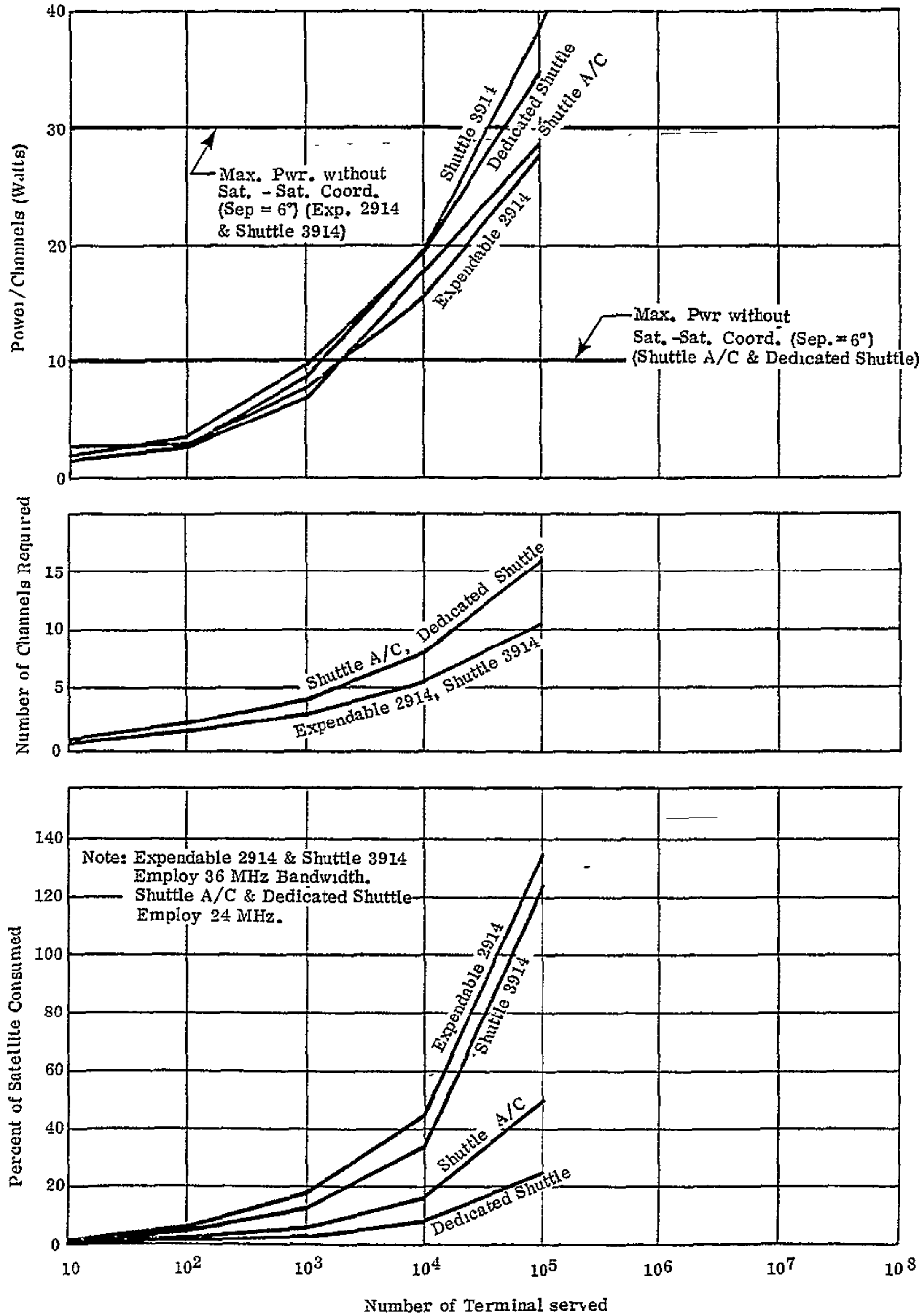


Figure 4-14. Satellite Power and Capacity Requirements (Ku-band, 4 Beams, .1% Link Outage (Compressed TV Distribution)

signal are comparatively small and inexpensive, non-redundant ground terminals and employed. Further, the satellite channel costs are not prorated among a large number of signals. These factors more than offset the channel output power backoff. The figure shows that the required number of satellite channels differs depending on whether small or large satellites are considered, because of the difference in the bandwidth selections. Three signals per channel can be handled in the small satellites while two signals per channel are handled by the large satellites. The total signal access requirements been defined to be 1, 4, 8, 16, and 32 for network sizes of 10, 10^2, 10^3, 10^4, and 10^5 terminals, respectively. Combining these requirements with the satellite bandwidth selections results in 0.3, 1.3, 2.7, 5.3, and 10.7 satellite channels required on small satellites, at network sizes of 10, 10^2, 10^3, 10^4, and 10^5 terminals, respectively. On large satellites 0.5, 2, 4, 8 and 16 satellite channels are required for network sizes of 10, 10^2, 10^3, 10^4 and 10^5 terminals, respectively.

The satellite capacity requirements, shown in Figure 4-14, are quite modest until a network size of 10^5 terminals is reached. Networks on the order of 10^2 to 10^4 are considered more appropriate for this service. Its best application is probably in the provision of educational and instructional television. Accordingly, a Shuttle 3914, or Shuttle Atlas-Centaur satellite appear adequate. The Ku-Band coordination limits, shown in the figure, are based on the four-beam satellite curve provided in Figure 3-5. However, the limits have been adjusted to reflect satellite output backoff and channel bandwidths other than 27MHz. In the case of the large satellites, the only adjustment needed is for satellite output backoff. Accordingly,

$$P_{Coord} = P_{Curve} + 1.6\text{dB for Shuttle A/C and Dedicated Shuttle satellites.}$$

In the case of the small satellites, adjustments must be made for both channel backoff and power, accordingly,

$$P_{Coord} = P_{Curve} + 5.1\text{dB} + 10 \log_{10}(36/27) \text{ or}$$

$$P_{Coord} = P_{Curve} + 6.4\text{dB for Expendable 2914 and Shuttle 3914 satellites.}$$

The S-Band power at the flux density limit, shown in Appendix 7, is determined from the basic equation developed in Section 4.3.A.2. As applied to this service, it becomes:

$$P_{SC}(\text{dB}) = -20 + 10 \log_{10}(W_S/4\text{x}10^3) - P'_{P/A}$$

$$+ M_{BO} + 10 \log_{10}(B_S/B_{SC})$$

where:

- W_S is the bandwidth of the digital signal (i.e., 9 MHz based on a bandwidth to bit rate ratio of 1.5)

- $P_{P/A}$ is the ratio of the peak power density of the $\left(\frac{\text{Sin X}}{\text{X}}\right)^2$ spectrum to the average power density across the signal bandwidth as expressed in dB. It is determined as follows:

  $P'_{P/A} = 10 \log 10\ P'_{Peak}/P'_{Ave}$ where P'_{Peak} is 1.04 as shown in the power density spectrum displayed in Figure 4-15.

$$P'_{AVE} = \left\{ \int_{-4.5\times10^6}^{4.5\times10^6} \left[\frac{\mathrm{Sin}(\pi f/6\times10^6)}{(\pi f/6\times10^6)} \right]^2 df \right\} \Big/ (9\times10^6) \text{ or}$$

$P'_{AVE} \approx 0.58871$; therefore

$P'_{P/A} \approx 2.5\text{dB}$

- $M_B = 5.1\text{dB}$
- $B_S = 12\text{MHz}$ is the signal center to signal center separation in the satellite
- $B_{SC} = 36\text{MHz}$ for all satellites

Accordingly:

$P_{SC} \approx 120$ watts

This is a high enough value that no spreading is required with the transponder power.

4.0 Satellite and Ground Terminal Cost Vs. Network Size

Average annual satellite and ground terminal costs as a function of network size for this service are illustrated in Figure 4-16. The sharp decrease in cost with increase in network size is in agreement with previous results. In this service, the S-Band flux density limits are not a factor in the cost tradeoffs with Ku-Band systems. In spite of this, the figure shows that the S-Band cost advantage tends to be less than in previous cases. Because satellite costs are more important in this service (see Section 4.3.D.6). The use of wider channel bandwidths may benefit the S-Band service and increase its cost advantage (see Section 4.3.D.1).

5.0 Ground Terminal Requirements

Variations in the Ku-Band ground terminal performance parameters as a function of increases in ground network size are depicted in Figure 4-17. Similar results for the S-Band terminals are given in Appendix 7. In the figure, G/T decreases

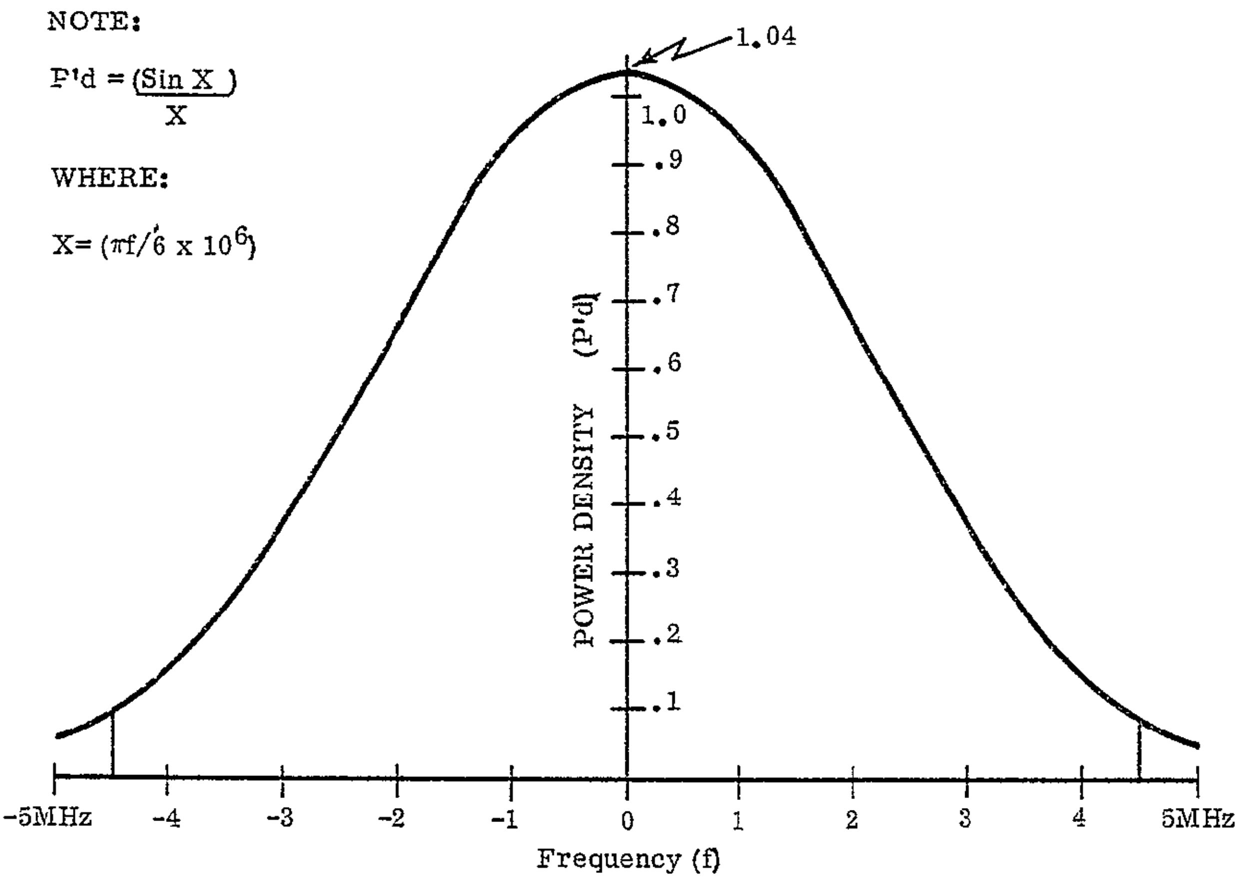


Figure 4-15. Power Density Spectrum for 6 Mbps Signal

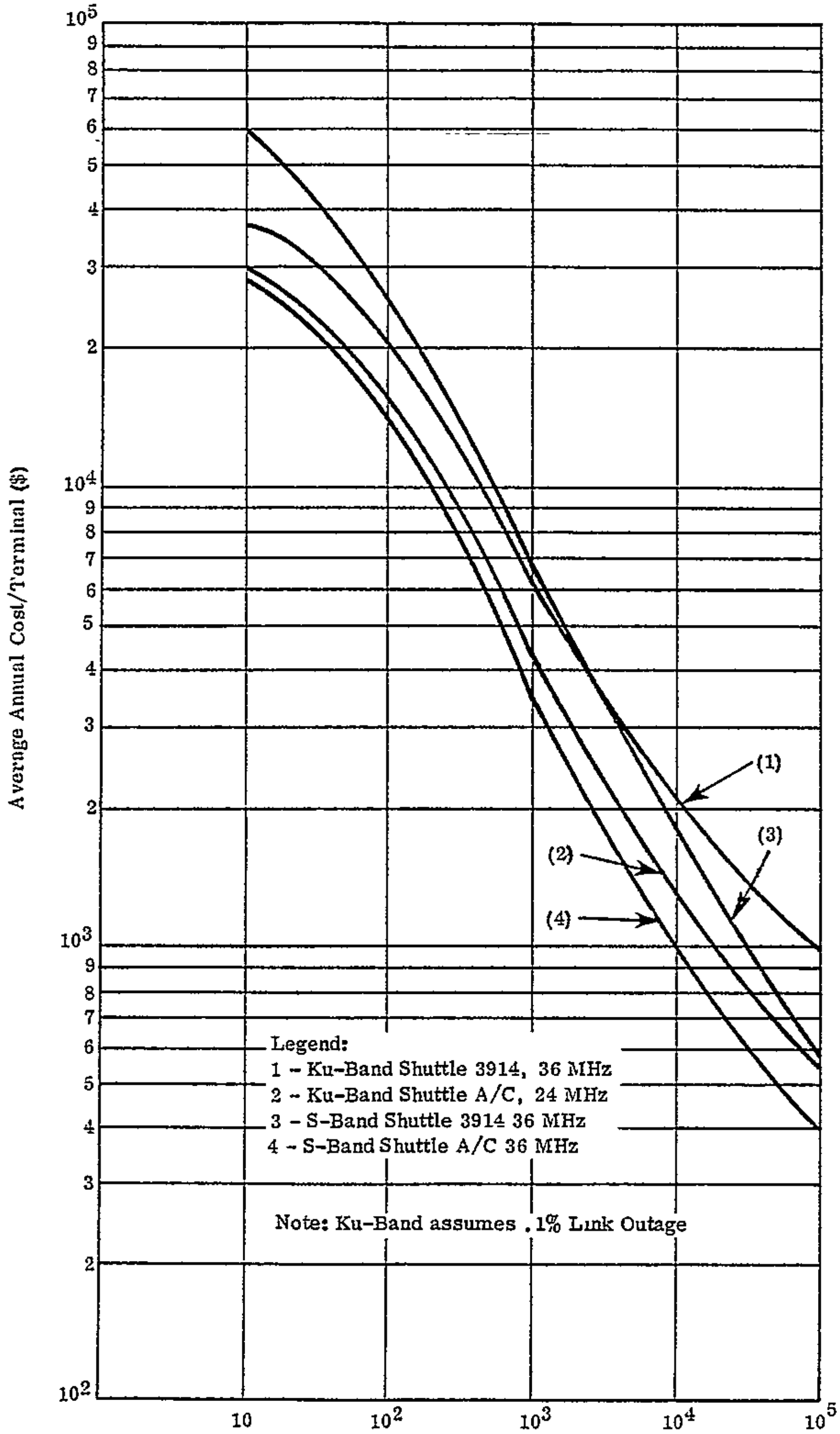


Figure 4-16. Average Annual Cost Versus Network Size and Frequency Band (4 Beam Satellite) (Compressed TV Distribution)

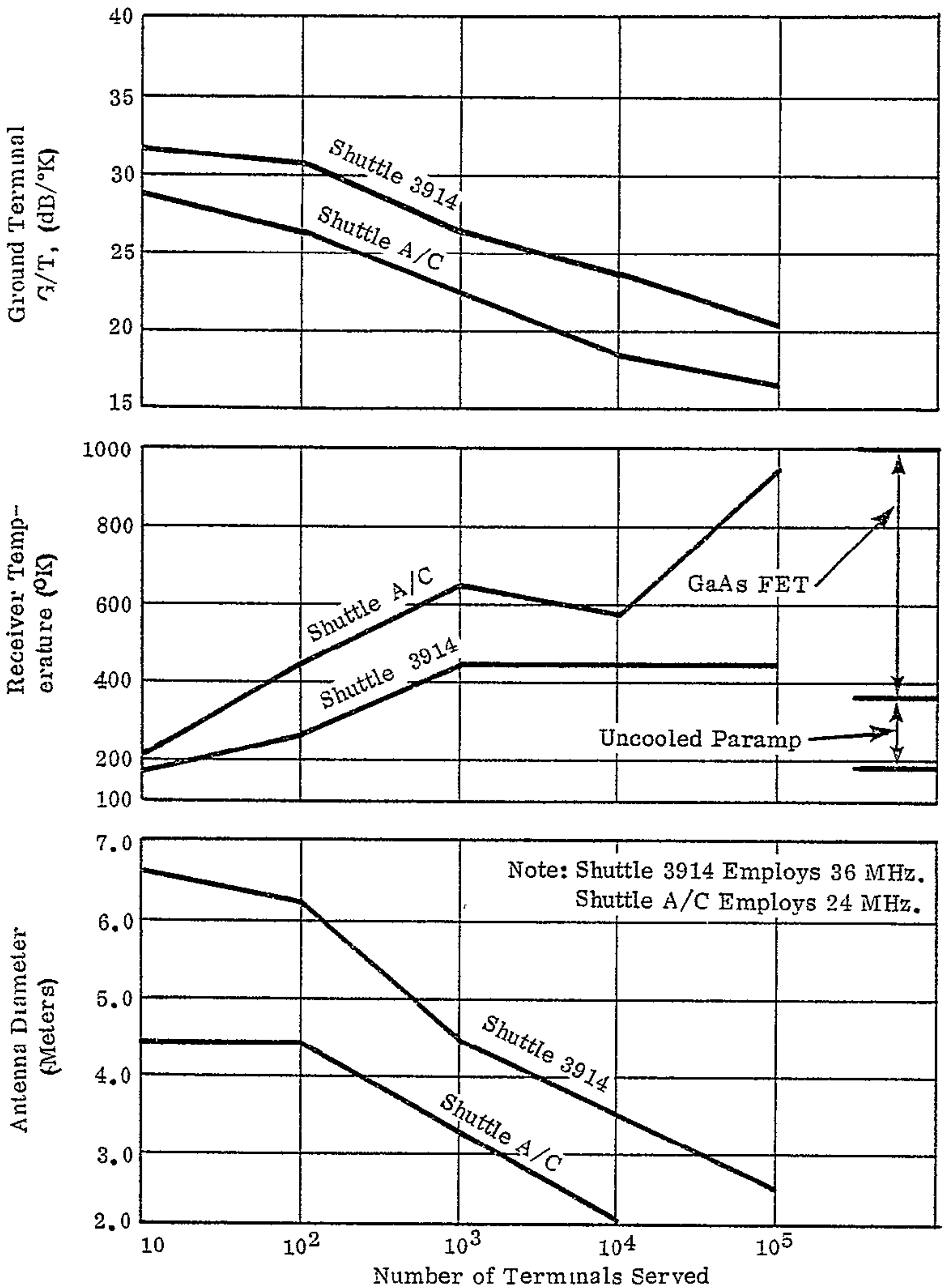


Figure 4-17. Ground Terminal Requirements (Ku-band, 4 Beam Satellite, 0.1% Link Outage) (Compressed TV Distribution)

as the network size increases, thus compensating for corresponding increases in satellite power. G/T decreases are accomplished through reductions in both antenna and receiver performances. The portions of the Shuttle A/C antenna curve, where the diameter is essentially constant, reflect sizes that are just below break points in the antenna cost versus diameter characteristics (see Section 3.6 and Appendix 1). The first-diameter-plateau is at 14.5 feet and the second is at 7.5 feet. As the antenna transitions to the second plateau the gain and cost reductions are such that it is cost-effective to use a higher performance receiver. In the case of the Shuttle 3914 curves, the trends tend to be fairly consistent. The leveling off in the rate of increase in the temperature curve for network sizes of 10^3 to 10^5 terminals, occurs because receiver cost reductions tend to be larger than antenna cost reductions as the production quantities increase. The figure shows that for a network of 10^4 terminals operating with a Shuttle Atlas Centaur satellite, a 2.3 meter (i.e., 7.5-foot) fixed pointed prime focus fed antenna and a 580°K GaAs FET receiver are optimum. Typical variations in G/T producing no more than a 10% increase in satellite and ground terminal costs are displayed in Table 4-26. The bounding parameters are read from the system optimization curves shown in Appendix 7. At the lower bound, when a Ku-Band Shuttle Atlas Centaur satellite operates with 10^4 terminals, a 7-foot antenna and a 950°K GaAs FET receiver can be used. The performance requirement is reduced further if the extra satellite antenna gain to the Southeast is eliminated resulting in an earth terminal G/T of about 13.5dB, which corresponds to a 7-foot antenna and a 1730°K diode mixer receiver. Table 4-26 also shows corresponding S-Band terminal parameters that reduce system costs by no more than 10%. As in the case of previous receive only systems, the S-Band antenna diameter generally tends to be smaller than that at Ku-Band while the receiver requirements are more stringent (see Section 4.3.A.4 for the reason). This is not a rigid rule since the tradeoffs relative to the satellite are not the same at the 10% cost increase point (i.e., the S-Band optimization curves tend to be broader at the minimum). In this case, flux density limits are not a factor in S-Band results.

6.0 Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items, are summarized in Table 4-27. Annual costs for a four-beam Ku-Band Shuttle Atlas Centaur satellite serving a network of 10^4 terminals, is about $7,060. This amounts to about $590 per month or less than $6 per student per month if 100 pupils are served in an educational TV system. Corresponding S-Band costs are slightly less (i.e., $6,730 annually). The fixed item costs are entirely equipment costs, which are broken out in detail in Appendix 1.

When the costs of Table 4-27 are compared with comparable conventional TV service costs (see TV Direct to the User, Section 4.3.B.5), it becomes obvious that this service is much too costly, because of the fixed equipment costs. TV coding/decoding to reduce the bandwidth does reduce the satellite and earth terminal costs, however, these reductions are insignificant compared to the cost increases introduced by the TV processing equipment. The table also shows that satellite costs can be a significant factor. However, earth terminal costs are not very important. This distribution of costs between the satellite and the ground terminals is further verified in the sensitivity analysis. This analysis, given in Appendix 7, considers independent ± 10dB variations in satellite and ground terminal cost with all other factors constant. The best hope of reducing costs

Table 4-26. Bounds on Ground Terminal G/T, Receiver Temperature, and Antenna Diameter (4 beam satellite) (Compressed TV Distribution)

Frequency	Launch Vehicle	Parameter	Lower Bound	Upper Bound
Ku-band (1)	Shuttle 3914 (2)	G/T (dB/°K)	26.0	34.5
		Received Temp(°K)	450	150
		Ant. Dia. (meters)	4.5	7.0
	Shuttle A/C (2)	G/T (dB/°K)	16.0	21.0
		Received Temp (°K)	950	745
		Ant. Dia. (meters)	2.0	3.0
S-band (3)	Shuttle 3914 (2)	G/T (dB/°K)	9.0	19.5
		Received Temp(°K)	275	160
		Ant. Dia. (meters	2.5	6.0
	Shuttle A/C (2)	G/T (dB/°K)	2.5	8.5
		Received Temp. (°K)	755	460
		Ant. Dia. (Meters)	2.0	3.0

Notes:

1) 0.1% Link outage assumed, 36 MHz for Shuttle 3914, 4 MHz for Shuttle A/C.

2) Shuttle 3914 assumes 10^2 terminals; Shuttle A/C assumes 10^4 terminals.

3) 36 MHz bandwidth assumed for both launchers.

Table 4-27. Total Average Annual Cost per Terminal (4 Beam Satellite) (Compressed TV Distribution)

Freq.	Launch Vehicle	Total Annual Cost ($)	Percent of Cost In:		
			Satellite	Gnd Terminal	Fixed
Ku-band (1)	Shuttle 3914 (2)	26,860	48	17	35
	Shuttle A/C (2)	7,060	15	4	81
S-Band (3)	Shuttle 3914 (2)	33,945	67	5	28
	Shuttle A/C (2)	6,730	9	6	85

Note: (1) 0.1% link outage, 36 MHz bandwidth for 3914, 24 MHz bandwidth for A/C.

(2) 10^2 terminals for 3914, 10^4 terminals for A/C

(3) 36 MHz bandwidth for both launches.

lies in considering cost performance/tradeoffs on the TV bandwidth compression equipment. An extensive survey of vendors could not be conducted during this study, the state-of-the-art in picture signal coding/decoding, is still evolving, and quantity production of hardware is non-existent. However, impact of LSI is considered in the interface equipment cost (see Appendix 1). Consequently, there is no reason to expect substantial cost decreases. However, the magnitude of these decreases will have to be large before a viable broadcast service application can exist. Wider satellite channel bandwidths, S-Band operation, bigger satellites, longer life and higher reliability satellites, shuttle optimized satellites, higher efficiency solar arrays in space, and the use of ion jets on spacecraft can also be of some help in reducing costs.

E. FM VOICE/MUSIC DIRECT TO THE USER

1.0 Average Annual Cost Versus Satellite Channel Bandwidth

The satellite channel bandwidth variations and their cost implications for a Ku-Band system are summarized in Table 4-28. Similar results, for S-Band and UHF systems, are given in Appendix 7. The table indicates that a 2 MHz bandwidth is optimum and this is the bandwidth carried forward in the evaluations. The same is true at S-Band and UHF. Such a narrow bandwidth selection results from this being a power starved service. The number of users per satellite signal is large since only four time zone radio channels provide direct service to a large number of users. Further, even at a satellite channel bandwidth of 2 MHz there is sufficient bandwidth for 20 radio channels, e.g., each broadcast signal is allocated only 1/20th of the channel power. As a result, it appears that optimized results have not been obtained for networks of 10^5 terminals and higher. Still narrower channel bandwidths might be more optimum.

2.0 Average Annual Cost Vs. Number of Beams Per Satellite

The system cost comparisons between one and four-beam Ku-Band satellites are given in Table 4-29. Similar cost comparisons for S-Band and UHF satellites are given in Appendix 7. In the cases of the one-beam satellite configurations at network sizes of 10^7 terminals, an 8MHz satellite channel bandwidth is used for the purpose of equalizing the one and four-beam comparison. At these network sizes, neither the one or four-beam satellites have enough power to reach system optimization. However, if 2MHz bandwidths are used on both systems, the one-beam approach comes much closer to optimization. In contrast, the four-beam satellite can select no fewer than four 2MHz channels. Therefore, all its available power is spread over 8MHz of bandwidth. Assuming an 8MHz channel for the one-beam satellite in the power limited situations equalizes the comparison between the two. Note that the problem here is simply one of equalizing the portion of the satellite payload allocated to the service. Further, this bandwidth is optimum at S-Band and UHF when the satellite or network size is large. This is quite similar to the results for the other receive only services. Accordingly, the four-beam approach is selected for further consideration in all cases.

Table 4-28. Average Annual Cost Vs. Bandwidth (Ku-band Satellite, .1% Link Outage) (Radio Broadcast)

Launch Vehicle	B_{SC}* MHz	1 Beam 10^4	1 Beam 10^6	4 Beams 10^4	4 Beams 10^6
Shuttle 3914	2	600	150	435	160
	8	595	215	605	280
	16	750	295	875	430
	32	1,145	500	1,315	625
Shuttle A/C	2	510	125	380	130
	8	490	160	410	185
	16	510	195	520	245
	32	625	260	765	365

* Satellite transponder bandwidth

Table 4-29. Average Annual Cost/Terminal Vs. Number of Beams/Satellite (Ku-band Satellite) (Compressed TV Distribution)

	Launch Vehicle	10^3 Term.(1)		10^7 Term.	
		0.1% Outage	0.05% Outage	0.1% Outage	0.05% Outage
2 Beams	Exp 2914	$ 2,030	$ 2,480	$ 170(2)	$ 195(2)
	Exp 3914	1,850	2,330	145(2)	165(2)
	Shuttle 3914	1,675	2,125	145(2)	165(2)
	Exp A/C	1,510	1,890	120(2)	130(2)
	Shuttle A/C	1,365	1,710	120(2)	130(2)
	Ded. Shuttle	1,135	1,405	100(2)	110(2)
4 Beams	Exp 2914	1,280	1,465	130(1)	125(1)
	Exp 3914	1,120	1,280	120(1)	115(1)
	Shuttle 3914	1,025	1,165	120(1)	180(1)
	Exp A/C	890	1,000	95(1)	130(1)
	Shuttle A/C	820	915	95(1)	130(1)
	Ded. Shuttle	700	770	65(1)	70(1)

Notes: (1) 2 MHz Bandwidth Employed
(2) 8 MHz Bandwidth Employed

3. Satellite Requirements

The Ku-band satellite power per channel as a function of the number of terminals in the network is given in Figure 4-18. Similar requirements for the S-band and UHF satellites are given in Appendix 7. As in previous receive-only services, the power per channel increases as the network and satellite size increases, (see Section 4.3.A.2 for reasons). Figure 4-18 clearly shows the Ku-band satellite power limitations for network sizes of 10^5 terminals and larger. The limitations are not as severe at S-band, where the Dedicated Shuttle satellite has adequate power up to and including a network size of 10^5 terminals. At UHF, both the Dedicated Shuttle and the Shuttle Atlas Centaur satellites supply enough power to optimize networks of up to 10^5 terminals but these also run out of power at 10^6 terminals. The figure clearly shows that these power limitations are primarily a satellite allocation problem because only about 5% of any satellite payload is consumed even though the channel power is at a maximum. Four signals access the satellite regardless of the size of the network. With a 2 MHz satellite channel bandwidth, 20 FM voice/radio signals can access a single channel. This means 1/5th of a satellite channel is needed regardless of the network size. The service can readily be handled by any of the satellites considered for network sizes up through 10^6 terminals, however, use of a Shuttle Atlas-Centaur makes the service more cost-effective. The Ku-band coordination limits, shown in the figure, are based on the four-beam satellite curve provided in Figure 3-5. However, the limits are adjusted to reflect the need for satellite output backoff and use of channel bandwidths other than 27 MHz. If the channel center-to-channel center frequency allocation for 2 MHz channels is 2.5 MHz, then:

$$P_{Coord} = P_{Curve} + 5.1 + 10 \log_{10}(2.5/27) \text{ or}$$

$$P_{Coord} = P_{Curve} - 5.2\text{dB}$$

Note that this limit assumes the 27 MHz spectrum is filled with radio broadcast or equivalent signals.

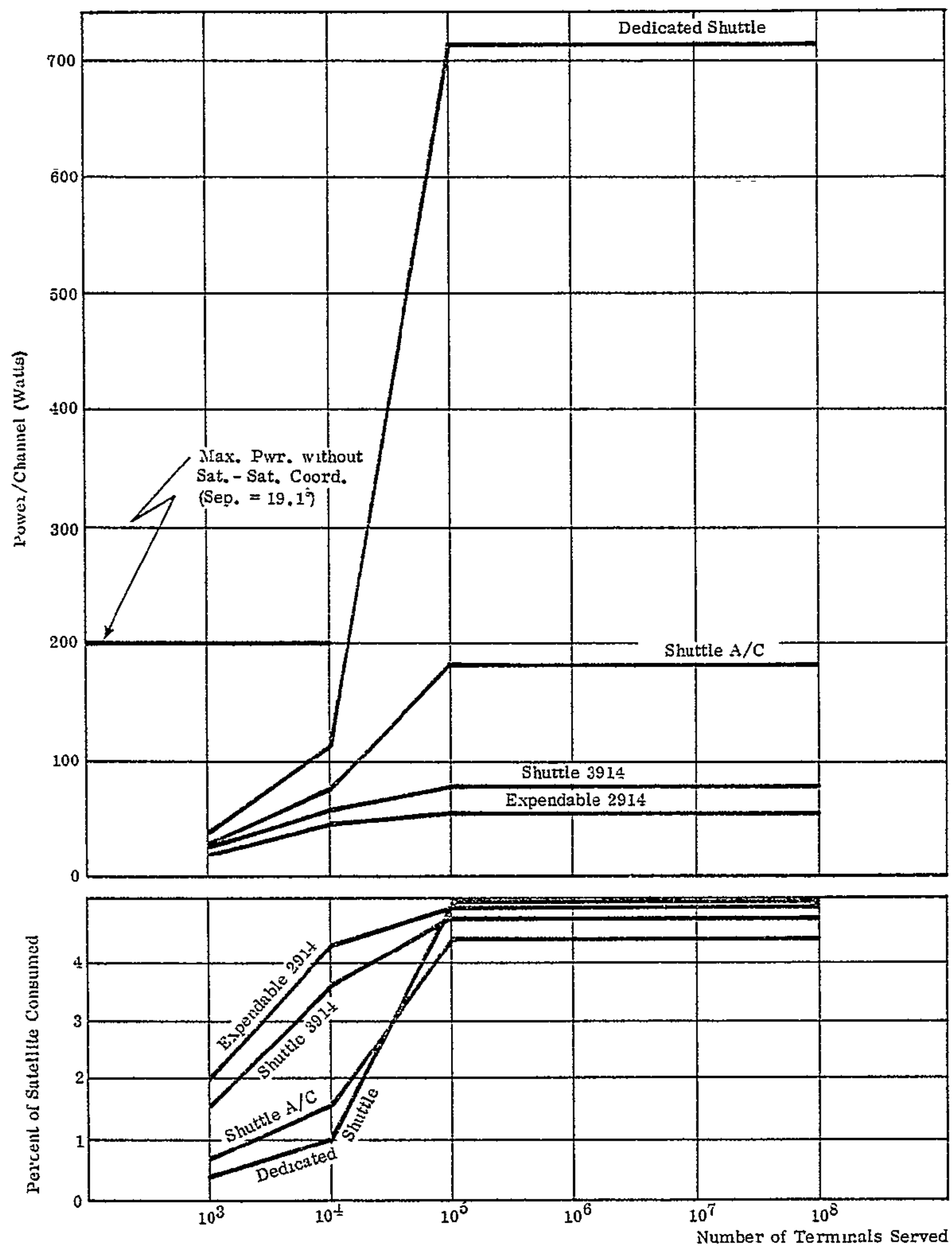
The S-band power at the flux density limit, shown in Appendix 7, is determined from the basic equation developed in Section 4.3.A.2; it is:

$$P_{SC}(\text{dB}) = -20 + 10 \log_{10}\left(\frac{W}{4}\right) - 5 \log_{10}\left(\frac{85+W}{85}\right) + M_{BO} + 10 \log_{10}\left(\frac{B_{SC}}{B_S}\right)$$

where:

- 85KHz is the signal bandwidth
- The satellite portion of the spreading loss

  i.e., $5 \log_{10}\left(\frac{85+W}{85}\right)$ is 0.75dB and the corresponding spreading, W, is 35KHz
- $M_{BO} = 5.1$dB
- $B_S = 100 \times 10^3$ Hz is the signal center to signal center separation in the satellite



Satellite Power and Capacity Requirements (Ku-Band, 4 Beams, .1% Link Outage, 2 MHz)

Figure 4-18. Satellite Power and Capacity Requirements
(Ku-Band, 4 Beams, .1% Link Outage, 2 MHz)
(Radio Broadcast)

- $B_{SC} = 2 \times 10^6$ Hz

Accordingly:

$P_{SC} \approx 5$ watts

4. Satellite and Ground Terminal Cost vs. Network Size

Average annual satellite and ground terminal costs as a function of network size are given in Figure 4-19. In this service, the normally observed rapid drop in receive only system cost as network size increases is mitigated by the limitations on satellite power. These limitations, resulting in non-optimum system configurations, start to be a factor at 10^5 to 10^6 terminals. The figure shows the flattening of the cost trend in this area. The S-band results do not take the satellite flux density limitations into consideration. There is considerable potential advantage in operating at the lower frequencies. Imposing the S-band flux density limitation produces the Ku-band/S-band cost comparison given in Table 4-30, based on the use of a four-beam Shuttle Atlas-Centaur satellite. The flux density limits impose a 5-watt power per channel constraint on the satellite and freeze the S-band ground terminal at a G/T of about 3.5 dB/°K. As indicated by the table the flux density limits increase the S-band costs over the entire range of network sizes. Further, the S-band costs are increased above those for Ku-band at network sizes greater than 10^4 terminals.

Table 4-30. Ku-Band/S-Band Cost (1) Comparison with Flux Density Limits Imposed Radio Broadcast

Frequency	Flux Limits	Number of Terminals					
		10^3	10^4	10^5	10^6	10^7	10^8
Ku-Band (2)	No	820	370	195	125	94	82
S-Band (2)	Yes	595	370	250	175	125	125
	No	510	210	90	37	36	

Notes: (1) Costs are average annual cost/user for the satellite and ground terminal.
(2) A four-beam Shuttle Atlas-Centaur sized satellite is used.

5. Ground Terminal Requirements

Variations in the Ku-band ground terminal performance parameters as a function of increases in the ground network size are depicted in Figure 4-20. Similar results for the S-band terminals are given in Appendix 7. The figure shows the G/T trends running counter to the corresponding satellite power per channel requirements (see Figure 4-18) as expected. This includes leveling off to a constant G/T, for network sizes of 10^5 terminals or greater, due to the satellite power per channel limit.

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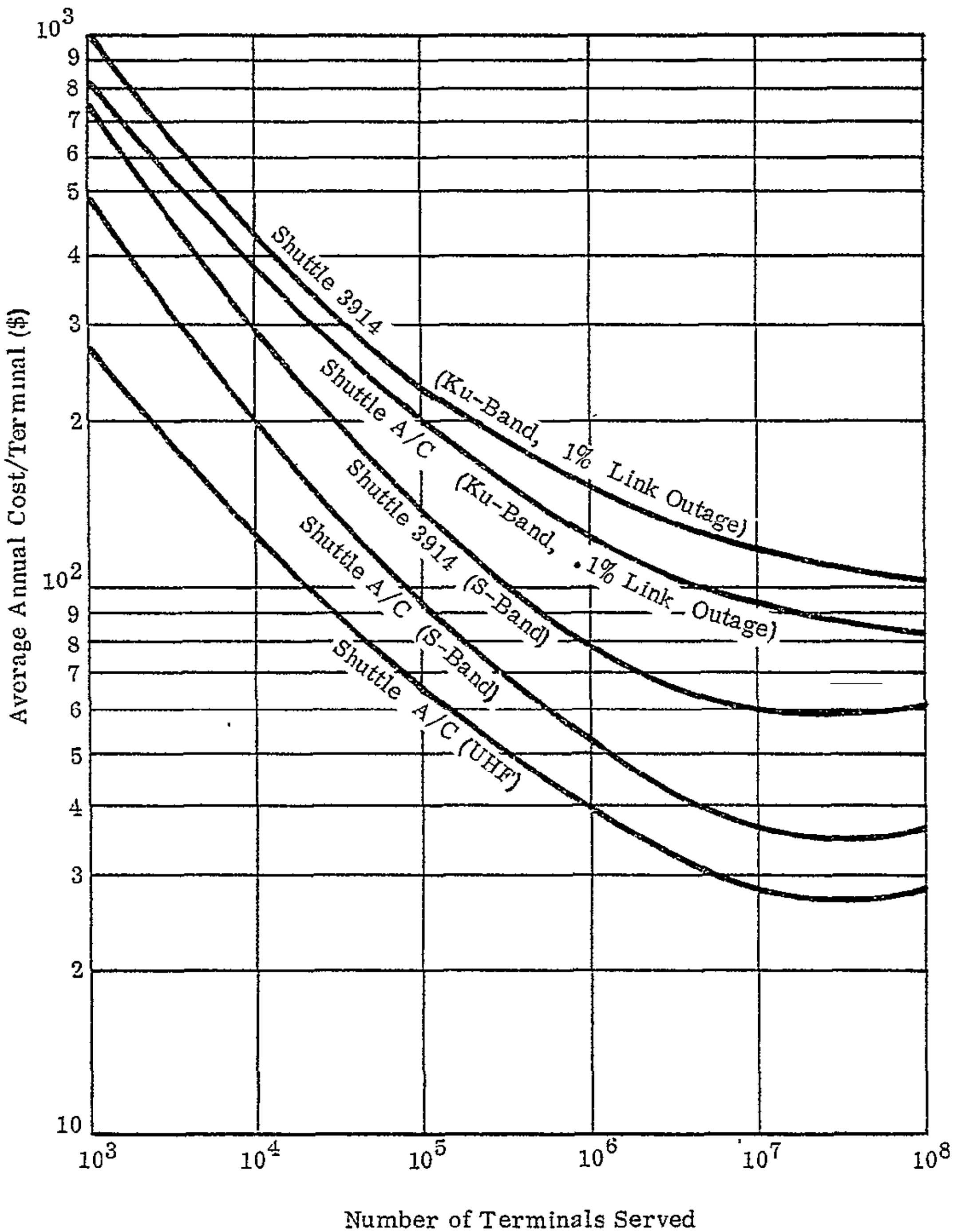

Figure 4-19. Average Annual Cost/Terminal vs. Number of Terminals Served (4 Beam Satellite, 2 MHz) (Radio Broadcast)

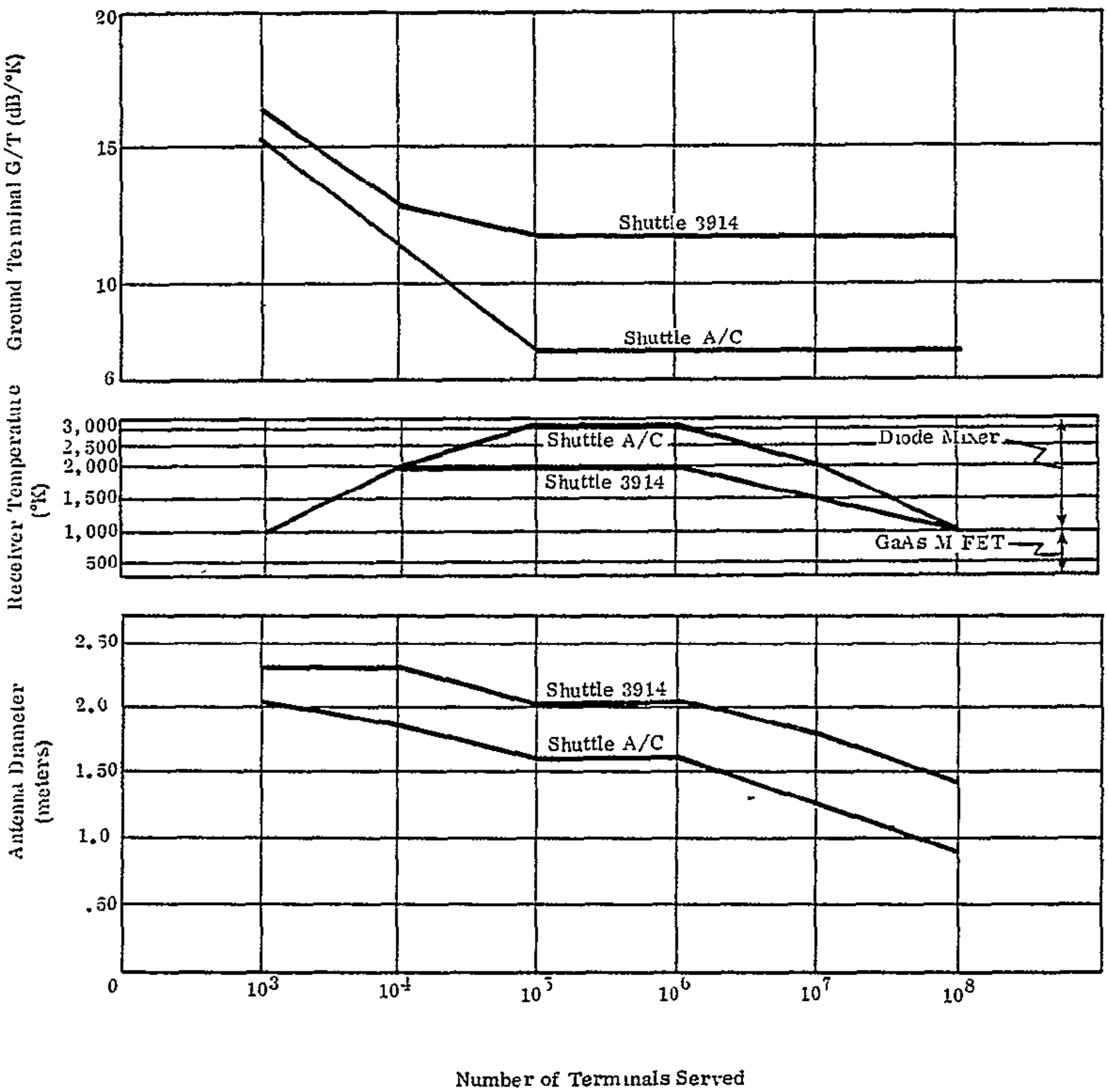

Figure 4-20. Ground Terminal Requirements Versus Number of Terminals Served (Ku-band, 4 Beam, 0.1% Link Outage, 2 MHz Sat. Chan. BW) (Radio Broadcast)

Decreases in G/T are accomplished by using both smaller antennas and higher noise temperature receivers. However, in the constant G/T region, the antenna size decreases while the receiver performance becomes more stringent, because receivers decrease in price more rapidly than antennas as the size of the buy increases.

The figure shows that for a network of 10^6 terminals operating with a Shuttle Atlas Centaur satellite, a 1.5 meter (i.e 5-foot) fixed pointed prime focus fed antenna and a 3,100 $^{\circ}$K diode mixer receiver are optimum. Notice once more that these performance requirements would be even less if more satellite power were available to achieve system optimization. Typical values of G/T producing no more than a 10% increase in satellite and ground terminal costs are not meaningful in this service. Reducing G/T requires the availability of more power in the satellite. The values obtained at a network size of 10^6 terminals represent both the lowest cost point and the minimum G/T on a non-optimum configuration. Nevertheless, the G/T increases causing the system cost to increase no more than 10% above the values found are tabulated in Appendix 7. Tabulations are provided for all three frequency bands of interest (i.e. Ku-band, S-band and UHF). Some reduction in the Ku-band G/T can be obtained without substantially affecting system cost if the extra satellite antenna gain to the Southeast is eliminated. The resultant earth terminal G/T is about 5 dB/$^{\circ}$K, which corresponds to a 4-foot fixed pointed prime focus fed antenna and a 3,100°K diode mixer receiver.

S-band and UHF ground terminal results, given in Appendix 7, repeat the tendancy observed in previous receive only services. The antenna diameters are less while the receiver performance requirements are more stringent than those of the corresponding Ku-band cases, (See Section 4.3.A.4 for the reason). When the S-band flux density limits are imposed, typical terminal parameters are: G/T = 3.5 dB/$^{\circ}$K, antenna diameter = 1.9 meters (i.e., a 6-foot fixed pointed prime focus fed parabolic reflector), and receiver temperature = 550°K (i.e., a GaAs FET low noise receiver).

6. Total System Cost Breakdown

Total system costs per terminal, including the fixed performance items, are summarized in Table 4-31. Annual costs, for a four-beam Ku-band Shuttle Atlas Centaur satellite serving a network of 10^6 terminals, is about $180, or about $15 per month per user, which is expensive for a radio service. The S-band costs, with the flux density limits imposed, are not dramatically different (i.e. $230 annually). However, if a UHF satellite allocation can be obtained, the costs are about $85 annually or about $7 per month per user, which is more reasonable. Note that none of these results are optimized values due to the satellite power limitations. Consequently, there is reason to believe that an acceptable service may be provided at a reasonable cost. Notice that even the indicated costs are significantly less than those for the TV Direct to the User service, (see Section 4.3.B.5). The fixed costs indicated in Table 4-31 are entirely equipment costs, and are broken out in detail in Appendix 1. The table shows that ground terminal and fixed equipment costs are the significant items in this service; satellite costs are not important. This distribution of costs between the satellite and the ground terminals is further verified in the sensitivity analysis. Results of this analysis are given in Appendix 7 considering $\pm$ 10 dB variations in satellite and ground terminal costs with all other factors constant.

Table 4-31. Breakdown of Total Average Annual Cost/Terminal (Radio Broadcast)

Launch Vehicle	Number Terminals	Freq-uency	Total Annual Cost ($)	Percent of Cost		
				Satellite	Ground Terminal	Fixed
Shuttle 3914(2)	10^4	Ku-band 1% Link Outage	560	17	61	22
		S-band	405	17	52	31
		UHF(1)	260	6	46	48
Shuttle A/C(2)	10^6	Ku-band 1% Link Outage	180	1	71	28
		S-band	105	2	50	48
		UHF	85	2	39	59

Note: 1) Shuttle A/C only considered for UHF at 10^4.

2) 4 beam satellite and 2 MHz bandwidth employed.

The first step to reduce system costs is to allocate more satellite power than permitted in the present model and obtain optimized system costs and performance parameters. Beyond this it appears that operating at lower frequencies without restrictions on radiated satellite power density offers the best hope of reducing costs. Fixed equipment costs are those of a threshold extension demodulator interfacing at IF. The cost of this technology decreases modestly as the buy size increases. Further, the oplimized satellite and ground terminal costs decrease significantly as the network size increases. Therefore, the deployment of large networks (e.g. 10^7 terminals) and operation of a big satellite (e.g., the Dedicated Shuttle) can produce significant reductions in per user costs.

SECTION 5

ORBIT CAPACITY CONSIDERATIONS

5.1 INTRODUCTION

The objective of this section is to determine the communications capacity of broadcast and fixed service satellites in terms of half duplex channels of Voice, TV and data in the K, S and UHF bands. No weight and/or power limitations are imposed and also it is assumed that the uplink power does not limit the capacity.

A. METHODOLOGY

The methodology that has been used in the capacity configurations is given here briefly in a descriptive manner. The details and underlying mathematical and computational methods are separated and included in Appendix 6. Various system and modulation parameters are also included there.

In the capacity computations, the effect of both thermal noise and interference is considered. The thermal noise depends upon the link parameters of the communication satellite system while the interference noise depends upon the RF interference that the link experiences from other communications satellite systems through antenna sidelobes. The thermal noise and the interference are first determined at the receiver input and their effect is subsequently translated into the baseband. The baseband quality is fixed at a preset value and the capacity that can be supported in the presence of thermal noise and interference is computed. The computation of the capacity thus consists of the following steps for a given satellite separation:

- Computation of receiver input carrier/thermal noise ratio
- Computation of receiver input carrier/interference ratio
- Conversion of thermal noise into baseband effects
- Conversion of interference into baseband effects
- Adjustment of modulation parameters so that the resultant baseband effects of thermal noise and interference yield a preset communication quality.

The carrier/thermal noise ratio at the receiver input is determined in the normal manner by using various link parameters which include transmitter powers, antenna diameters, frequency, system noise temperatures, and bandwidth. This computation is made for the desired communications satellite system and the earth station receiver which is associated with it. This desired communications satellite system is assumed to be operating amongst other similar communications satellite systems which are the interfering communications satellite systems. The interference at the input to the desired receiver is computed by considering the various interfering communications satellite systems and adding the interference contribution due to each system. Both up and downlink interference contributions are considered in computing the resultant interference at the receiver input.

The pertinent stage in the communications system where the effects of RF input thermal noise and RF input interference are considered is the baseband in the case of Voice and TV. Since the quality is measured in baseband, the capacity computations have been based upon a criteria assigned to baseband quality. The capacity computations thus require that the baseband effects of RF thermal noise and interference be evaluated. For FDM-FM voice and FM-TV, the baseband effect of thermal noise is expressed in terms of noise transfer factor which yields baseband thermal noise when the RF carrier to thermal noise ratio is known; and the baseband effect of interference has been expressed in terms of interference transfer factor which yields the baseband interference noise when the RF carrier to interference ratio is known. The baseband effects due to the two causes are combined to yield the resultant baseband quality. For specified link parameters and intersatellite spacing of satellites in the orbital arc, the modulation parameters are varied so that the baseband quality becomes equal to the preset value. The capacity, at this point, is then computed. In digital transmission, the terms baseband effects or noise and interference transfer factors cannot be used. In the presence of interference. the digital carrier has to incur an expenditure of carrier power in order to resist the effect of interference in addition to that of noise. In the presence of RF thermal noise plus RF interference the E_b/N_o required for a given probability of error is more than that in the case of RF thermal noise alone. As a consequence, the supportable data rate or the capacity is governed by interference.

B. GEOMETRIC MODEL

The geometric parameters of the model pertain to satellites and earth terminals. The communications satellites are assumed to be located in geostationary equatorial orbital arc at uniform intersatellite angular spacing. The angular spacing is measured at the center of the Earth. The desired satellite is assumed to be located at 100^{o} W Longitude and the interfering satellites are located on either side at uniform spacing and there are equal numbers of them on either side. The satellite receive and transmit beams have been assumed to be coaxial beams, and the earth station transmit and receive antenna beams are perfectly aimed at the satellite. A transmitting and receiving terminal is associated with each satellite. Although the satellite stationkeeping effects are not considered in the computations, their effect on capacity and technology is discussed wherever pertinent.

5.2 GENERAL CONSIDERATIONS

A. SATELLITE SERVICES

The services considered in capacity computations are:

1. Single Carrier FDM-FM Voice
2. FM-TV
3. Single Carrier 4-phase PSK data

4. Multiple Carrier FDM-FM Voice

5. Multiple Carrier 4-phase PSK data

The modulation parameters associated with these have been included in Appendix 6.

B. SYSTEM MODEL

In computations, a homogeneous system model is considered which assumes that:

- All the satellites are located in geostationary orbit.
- The interfering satellites are located on either side of the desired satellite
- The satellites are uniformly spaced and the angular spacing is measured at the Earth's center.
- The satellites have identical characteristics.
- The carriers are identically modulated.
- The modulation parameters on each carrier are identical.
- All satellites have identical EIRPs

C. ANTENNA PATTERNS

Various antenna radiation patterns which enter into capacity computations are:

- Earth terminal receive pattern
- Earth terminal transmit patterns
- Satellite receive pattern
- Satellite transmit pattern

For all antenna diameters and wavelengths, the FCC radiation pattern is used.* However, computations have been made by modifying the sidelobe characteristics in order to evaluate the effect of different sidelobe characteristics. Specifically, computations with two modifications to the basic FCC pattern are considered. These meet the FCC profile until the sidelobe patterns are down X db from the mainlobe peaks and then remain constant where

* An illustrative comparison of the results obtained by using CCIR based model is given in Figures 5-5, 6 and 7.

Table 5-1. Cases Representing Antenna Sidelobe Models Used For Ground Terminal and Satellite Antennas

Case Number	Ground Terminal Antenna Sidelobe Model	Satellite Antenna Sidelobe Model
1	1	1
2	2	2
3	3	3
4	1	4
5	2	4
6	3	4

Note: The mathematical description of the sidelobe models is given in Appendix - 6.

(1) $X = 40$

and (2) $X = 60$

These three antenna sidelobe models are respectively denoted Model 1, 2 and 3. A fourth antenna sidelobe model derived from the CCIR antenna model and identified by number four (4) is also examined. The combinations of the earth terminal antenna sidelobe model and the satellite antenna sidelobe model used are identified by case numbers, as listed in Table 5-1.

D. INTERFERENCE CRITERIA (PREDETECTION)

When the receiver associated with a desired communications satellite is operating in the presence of other communication satellite systems, both thermal noise and interference are present at the receiver input. The predetection interference that is acceptable depends upon the baseband interference that can be accepted. In an interference limited environment when high capacity is the objective, limiting the baseband interference and hence the predetection interference even though the baseband interference may be well within the total quality objectives may not be the right strategy. From this viewpoint, when the baseband quality objectives are satisfied, the fixed resource of the geostationary orbit is better used by accepting varying amounts of thermal noise and interference noise into the baseband and letting their proportions vary to such an extent that baseband interference noise dominates the baseband thermal noise. In the capacity computations, this philosophy is adhered to. In the case of FDM-FM and FM-TV, where the modulation schemes exhibit threshold predetection interference, interference also determines whether the receiver is above or below threshold. When the sum of thermal noise and interference reaches a level which is 10 dB below the desired carrier, it has been assumed that threshold is reached and no further capacity computations are made. In the case of PSK transmission, however, such a restriction is not made. In this case data, capacity computations are made for carrier/(thermal noise + interference) ratios of less than 10dB.

E. INTERFERENCE CRITERIA (POST-DETECTION)

Before considering post-detection interference, it is necessary to describe how the bandwidth is used and how the modulation parameters are varied to make the system interference resistant.

In the case of FDM-FM voice, capacity computations are made on the basis of a 36 MHz fixed bandwidth which is typical of current satellites. In the multiple carrier FDM-FM case it is assumed that six (6) carriers are present in the satellite transponder each with a bandwidth of 6 MHz. Similar assumptions are made for PSK data. In the case of FM TV capacity is computed on the basis of variable bandwidth occupancy where it has been implicitly assumed that the allocated bandwidth can be divided amongst as many transponders as the number of FM TV channels that could possible by accommodated in that bandwidth. Modulation parameters are varied such that the quality is equal to a preset value in the presence of thermal and interference noise. In the case of FDM-FM voice, the number of voice channels per carrier is varied so that the resultant baseband signal to noise ratio when both thermal and interference noise are taken into account is equal to a preset value of 52 dB. The proportionate amount of thermal and interference noise

C-7

in the baseband channel is therefore not the same in all circumstances. In the case of FM TV the deviation and consequently bandwidth occupancy is varied so that the required amount of resistance to interference can be provided by the desired signal and the resulting quality is equal to a preset value of 56 dB. In the case of data, it is data rate which is varied so that the supportable data rate in a given bandwidth satisfies a preset error probability requirement of 10^{-4}.

F. "OTHER INTERFERENCE"

Besides interference due to other satellite systems, the possibility of "other interference" is explored. Frequency allocations for various communications services, terrestrial communications and studio to transmitter links and examination of site/frequency coordination procedures reveal that other interference can safely be ignored.

5.3 RESULTS AND TRADEOFFS

A. SERVICE CAPACITY

The communications capacity for cases characteristic of Broadcast and Fixed Services has been computed. Representative results revealing the factors which influence capacity are described in this section.(Figures 5-1 thru 5-22 and Tables 5-1 thru 5-19)The detailed parameters used in the computations are given in Appendix 6.

In order to express the orbit capacity, the three descriptors given in Table 5-2 are used.

Table 5-2. Capacity Descriptors

Information/ Modulation	Capacity Descriptor	Units
FDM-FM Voice	Voice channels in a specified bandwidth for a given inter-satellite spacing (Intersatellite spacing, degrees). (Specified bandwidth, MHz)	Voice Channels / Deg - MHZ
FM-TV	TV Channels in allocated band-width for a given intersatellite spacing (Intersatellite spacing, degrees)	TV Channels / Deg - Allocated BW - MHZ
Data	Data Rate in a specified bandwidth for a given intersatellite spacing (Intersatellite Spacing, degrees). (Specified BW, MHz)	Data Rate / Deg - MHZ

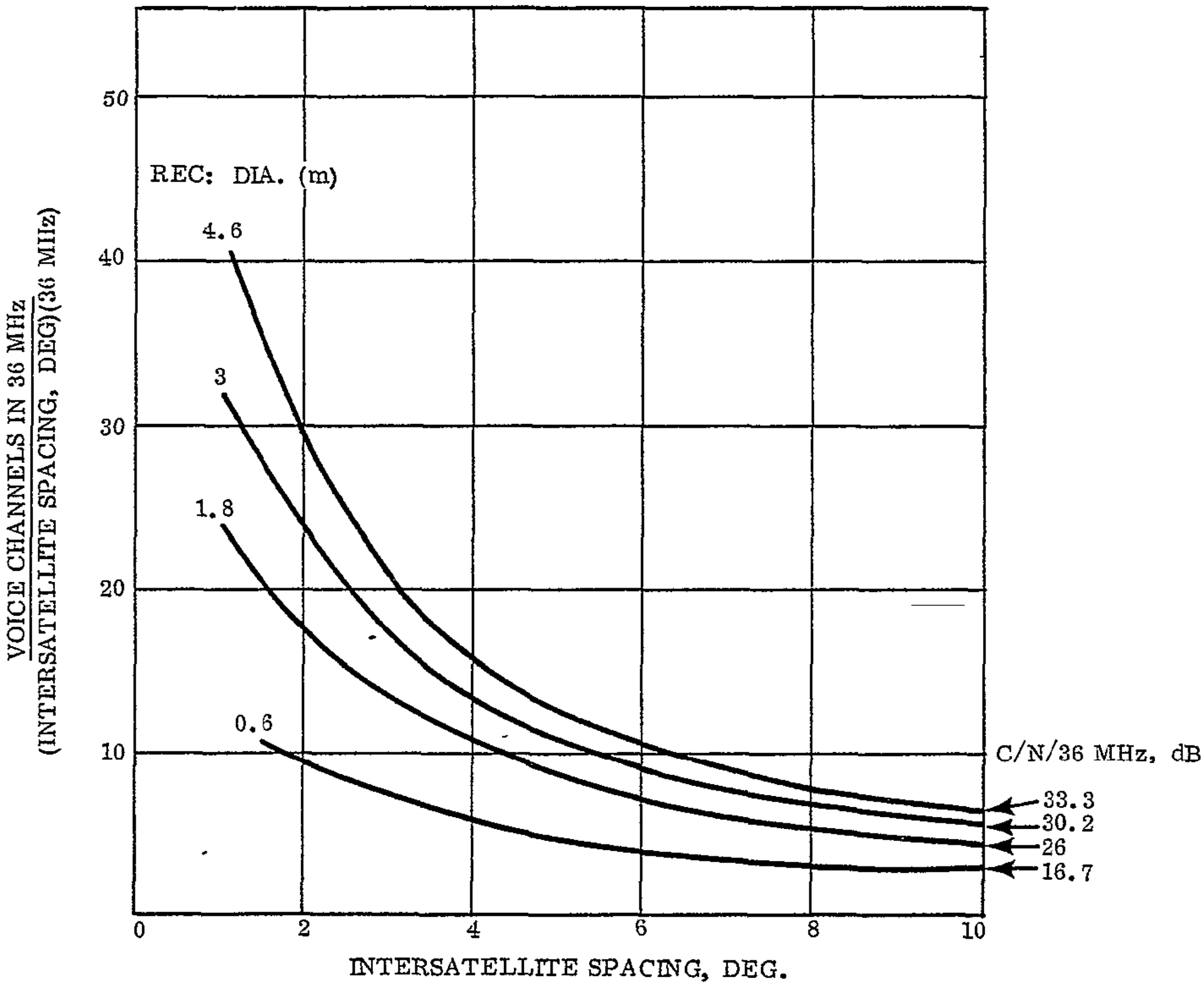

Figure 5-1. K-Band Broadcast Voice Capacity (Conus)
Sidelobe Model #1 and #3, Satellite EIRP = 57.5 dBw

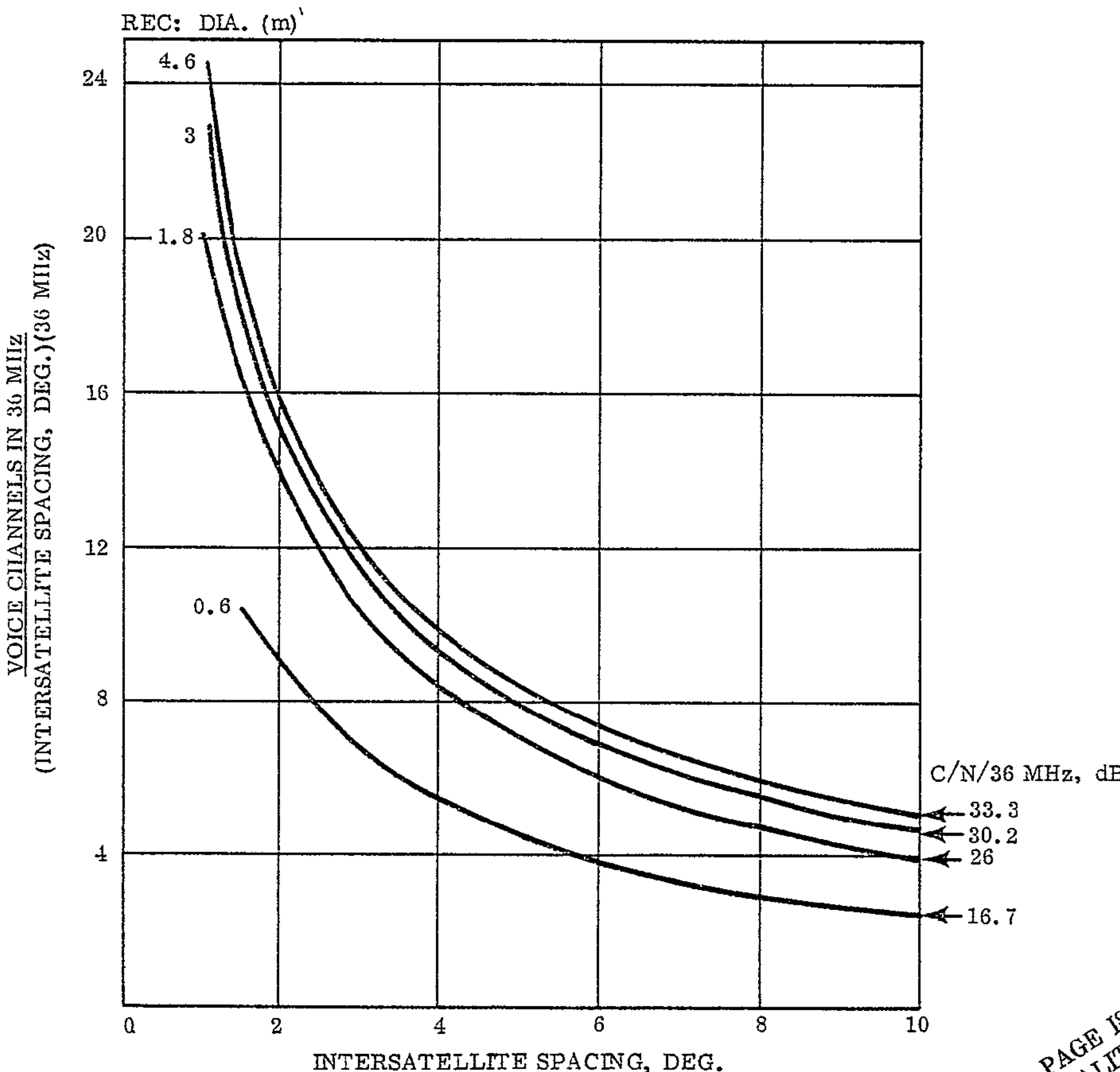

Figure 5-2. K-Band Broadcast Voice Capacity (Conus) Sidelobe Model Case #2, Satellite EIRP = 57.5 dBw

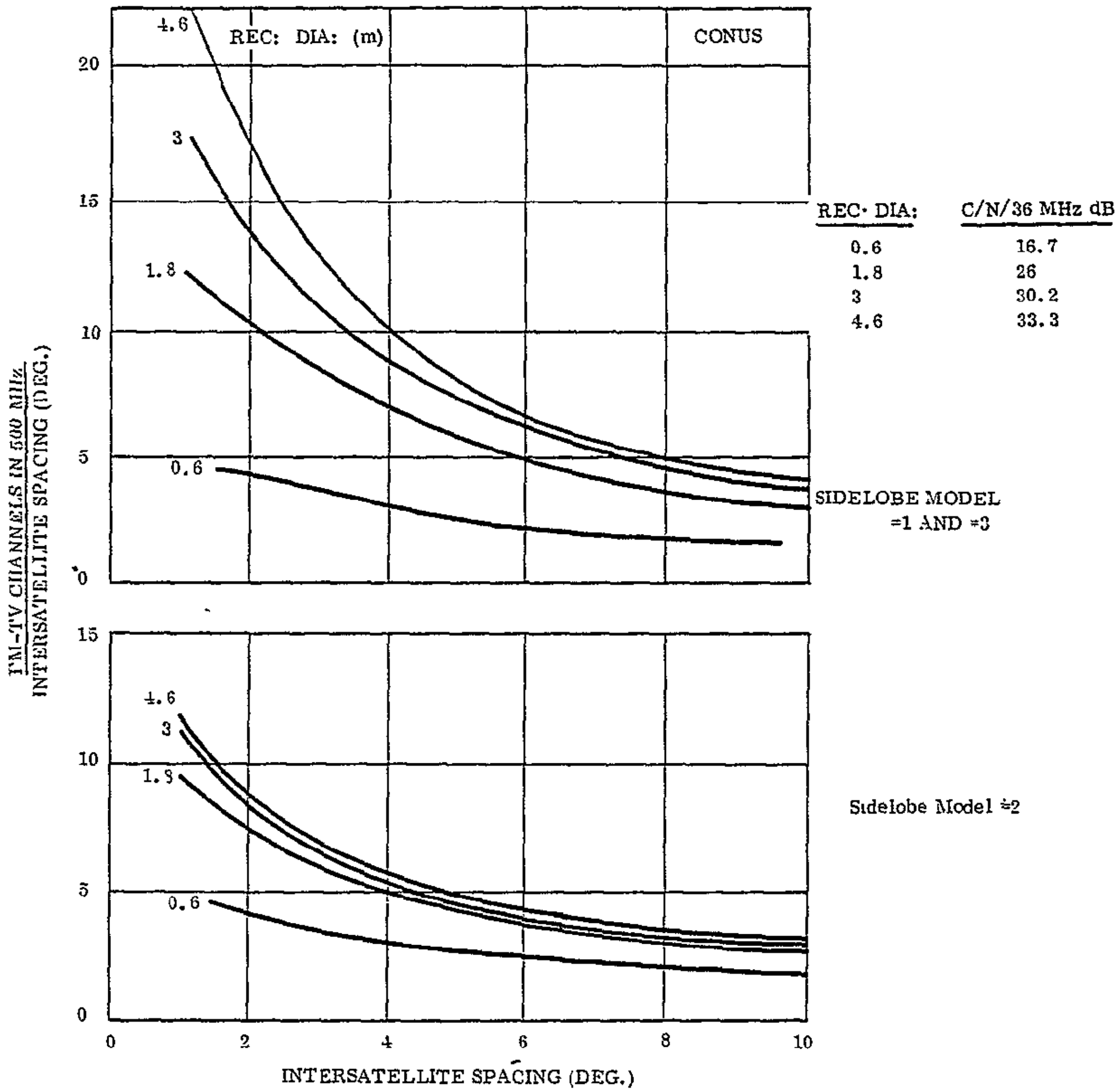

Figure 5-3. K-Band Broadcast TV Capacity
SAT EIRP = 57.5 dBW

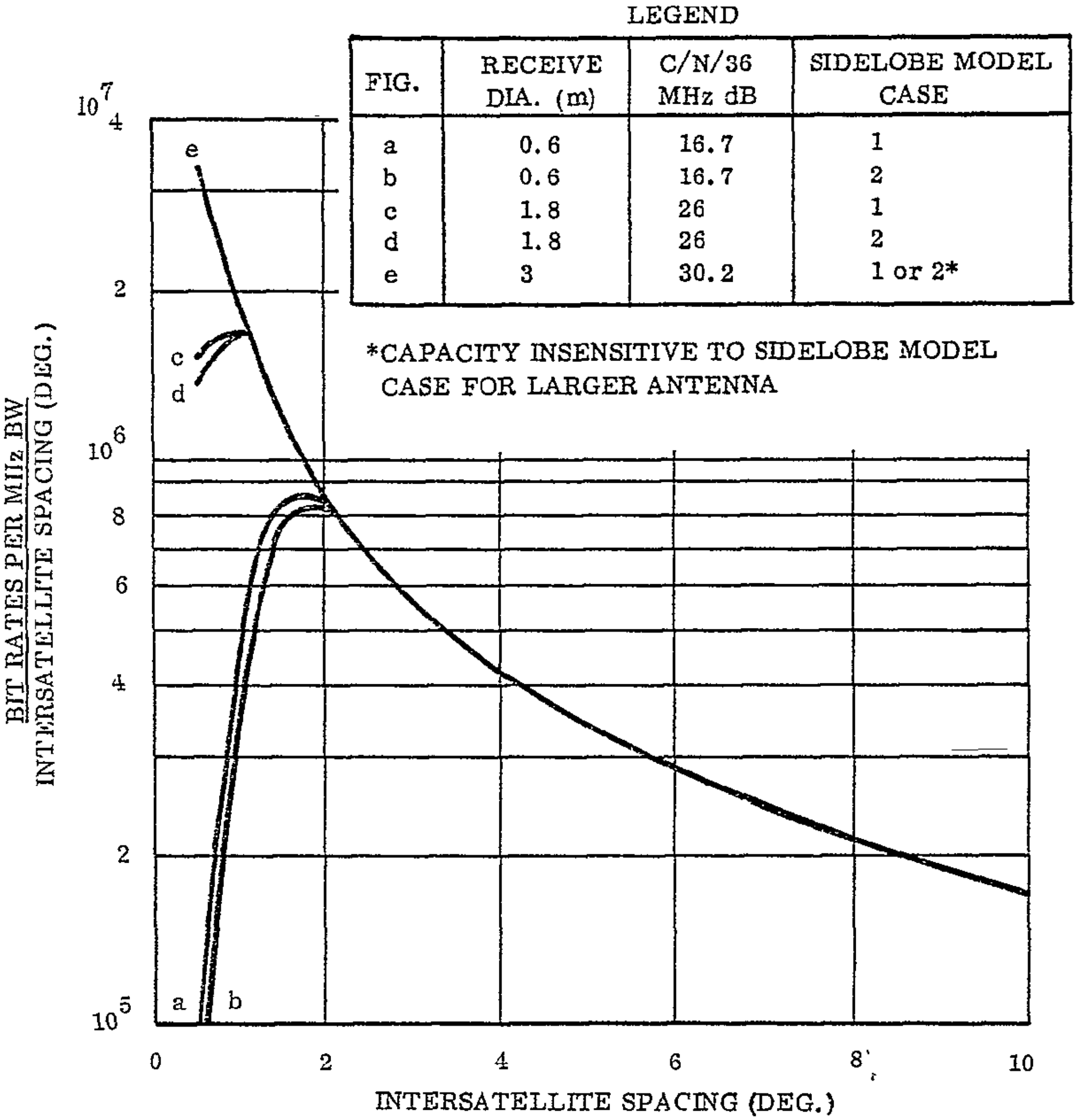

Figure 5-4. K-Band Data Capacity, Conus

SAT: EIRP = 57.5 dBw

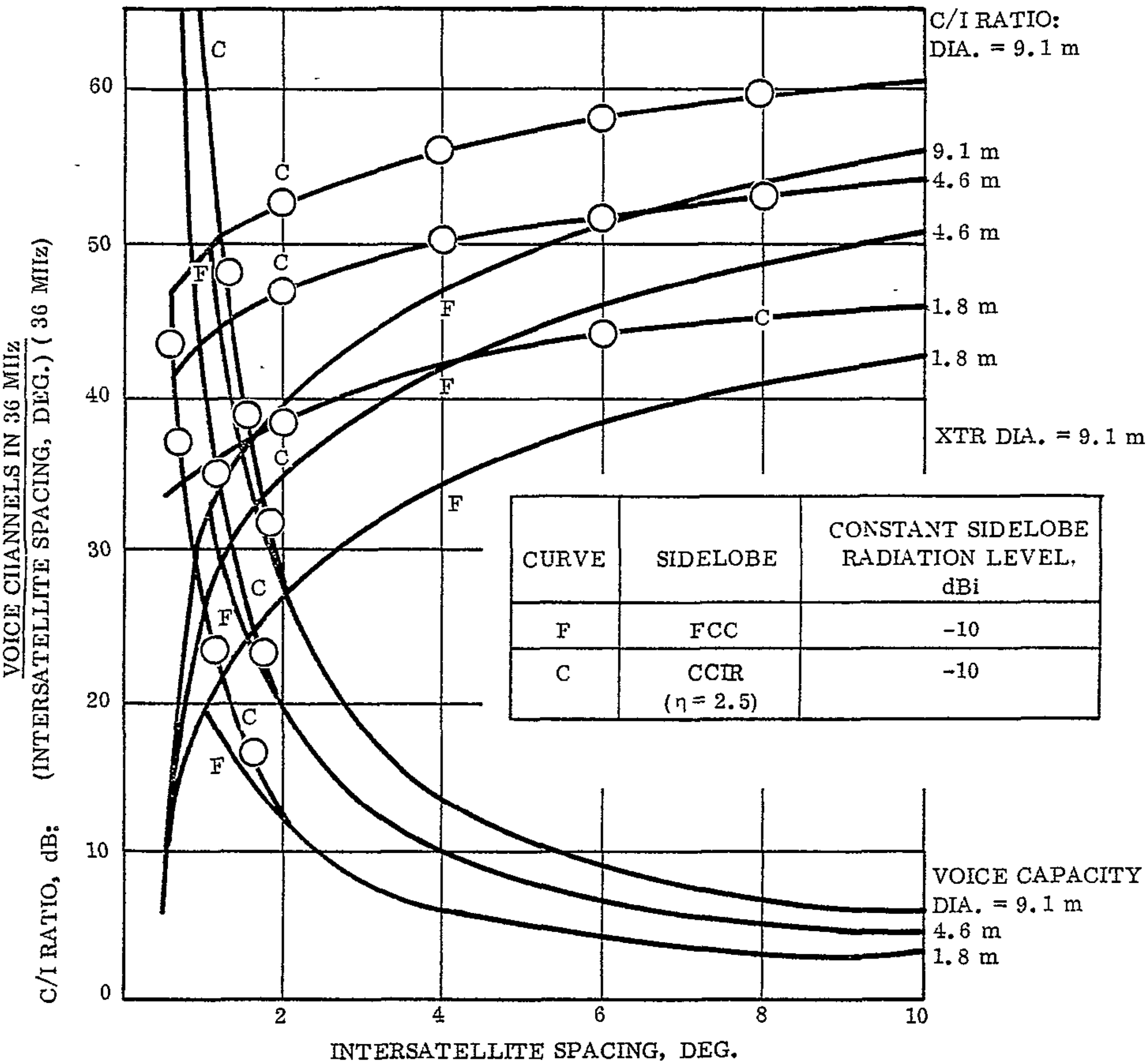

Figure 5-5. Comparative Voice Capacity with FCC and CCIR Sidelobes ; K-Band; SAT EIRP = 47.5 dBw

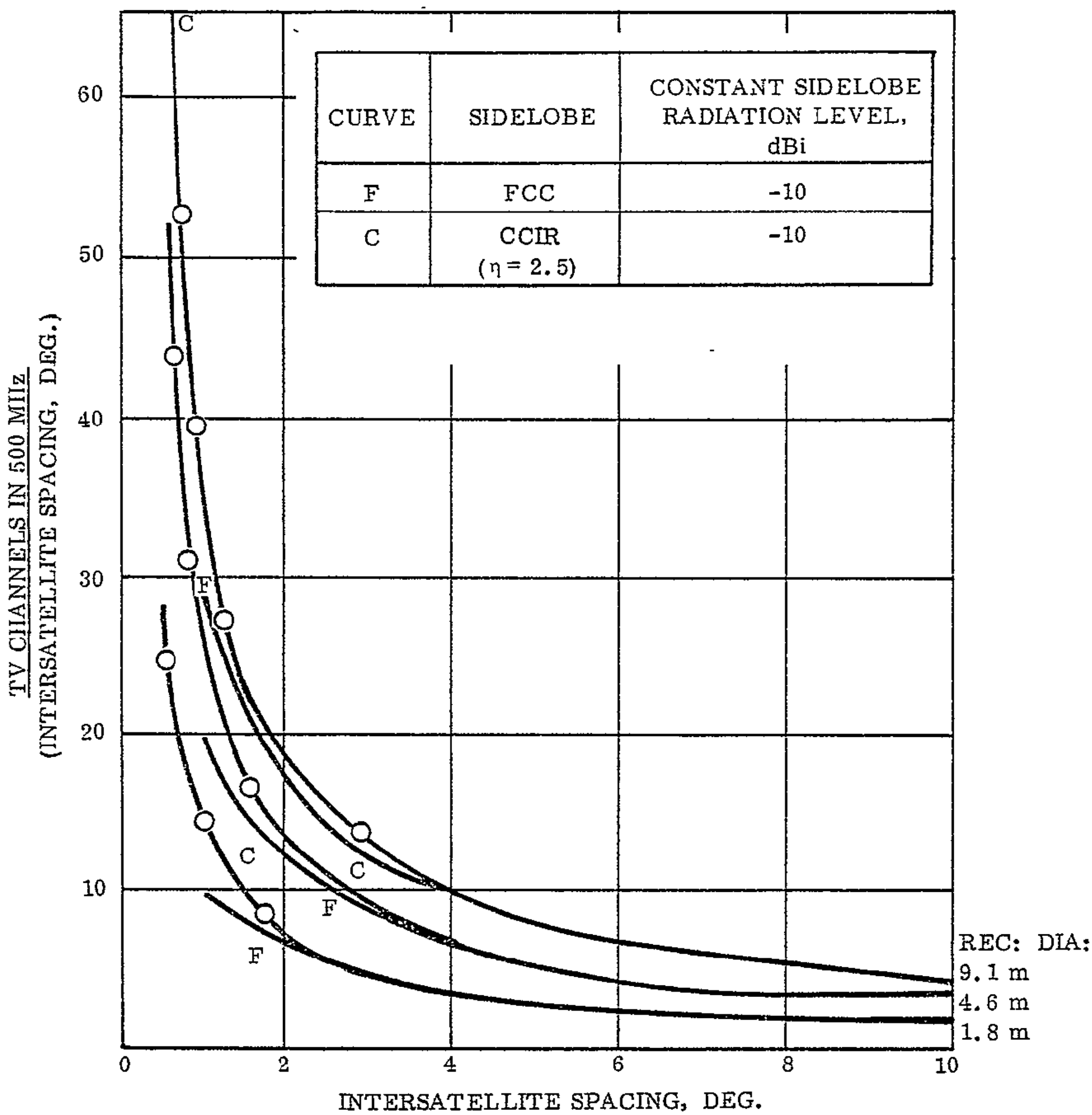

Figure 5-6. Comparative FM-TV Capacity with FCC and CCIR Sidelobes: K-Band; Sat EIRP = 47.5 dBw

CURVE	SIDELOBE	CONSTANT SIDELOBE RADIATION LEVEL, dBi	RECEIVE ANTENNA DIA. (m)
a	CCIR (η = 2.5)	-10	1.8 and 4.6
b	FCC	-10	4.6
c	FCC	-10	1.8

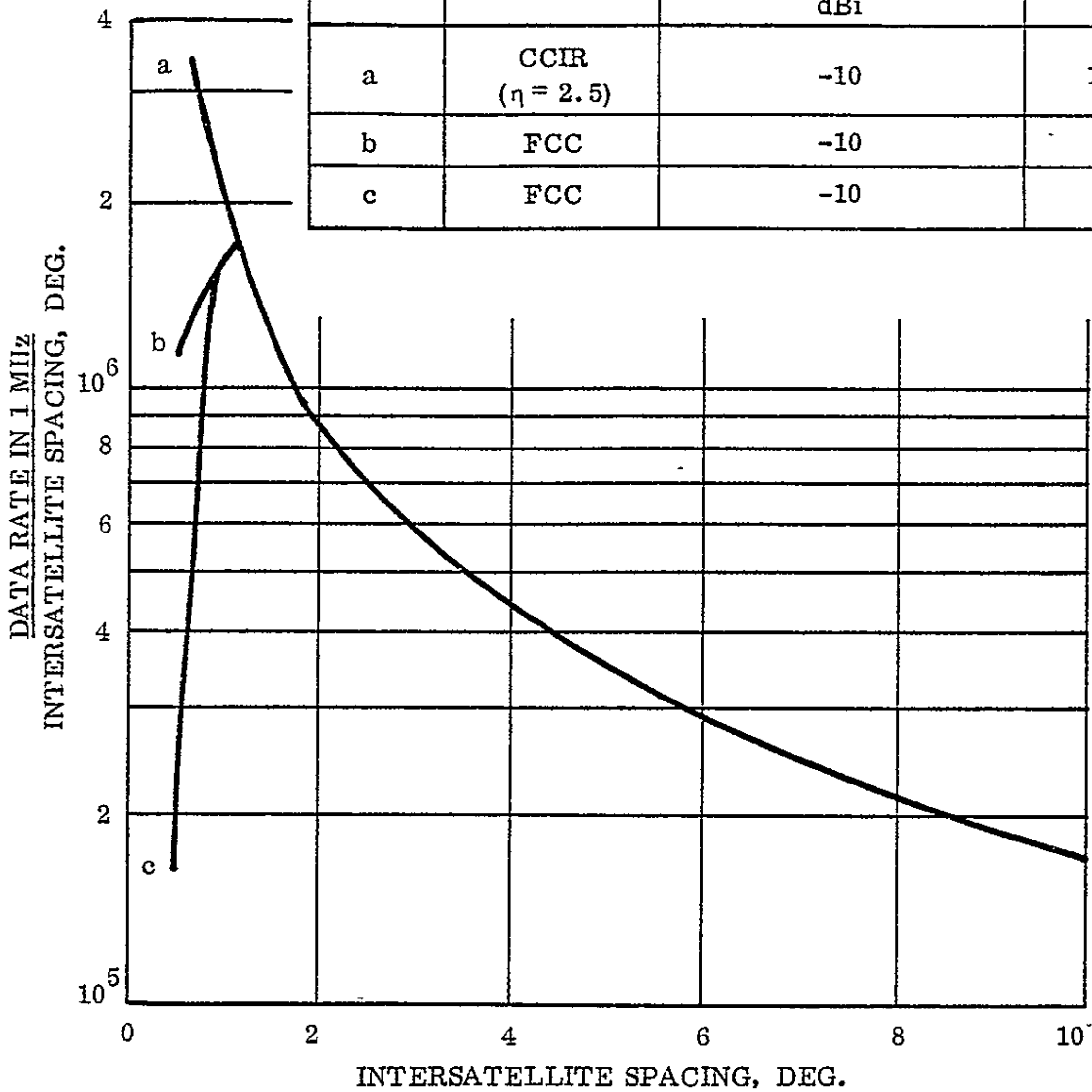

Figure 5-7. Comparative Data Capacity with FCC and CCIR Sidelobes; K-band; Sat. EIRP = 47.5 dBw

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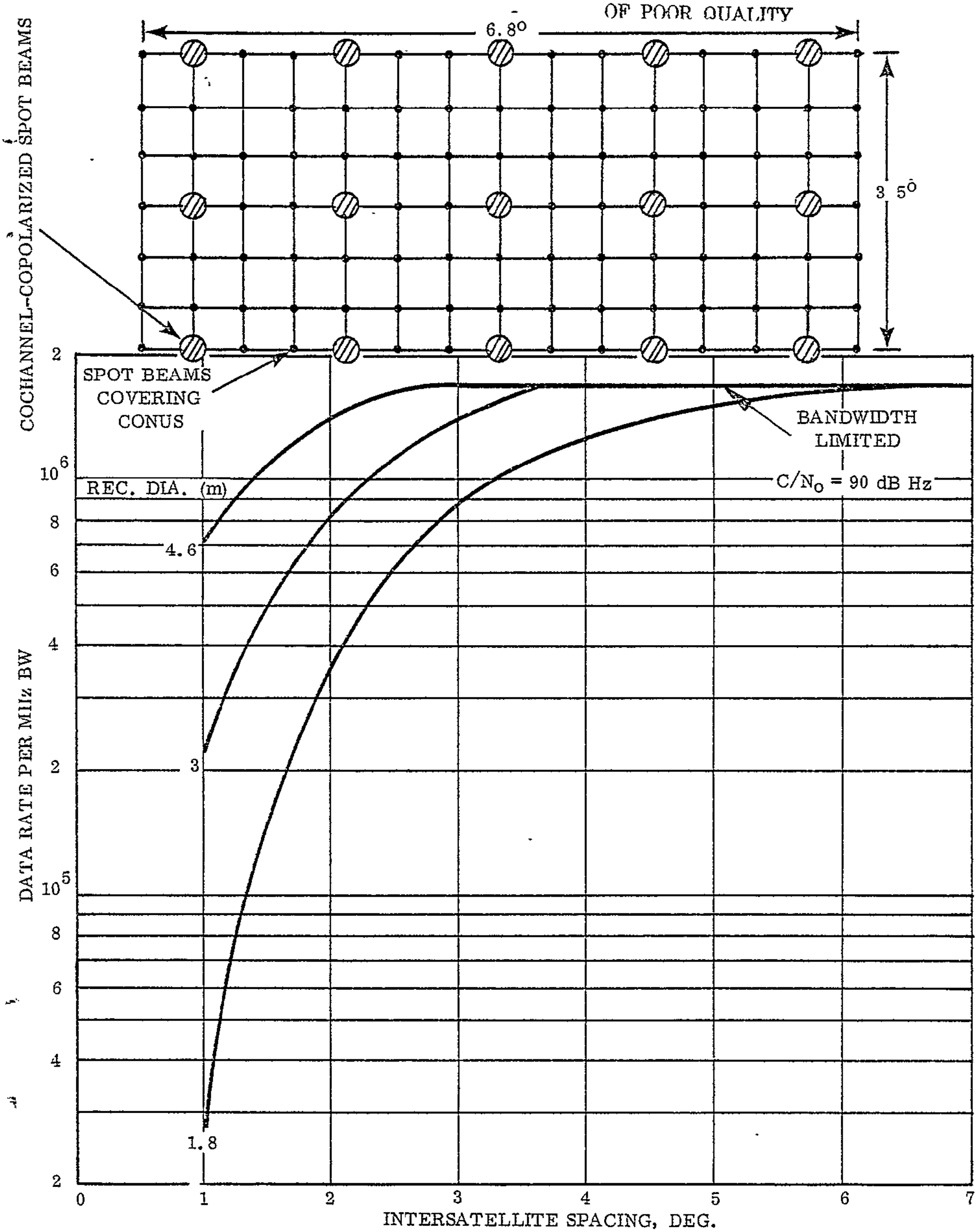


Figure 5-8. SS-TDMA Capacity for Various Receive Antennas

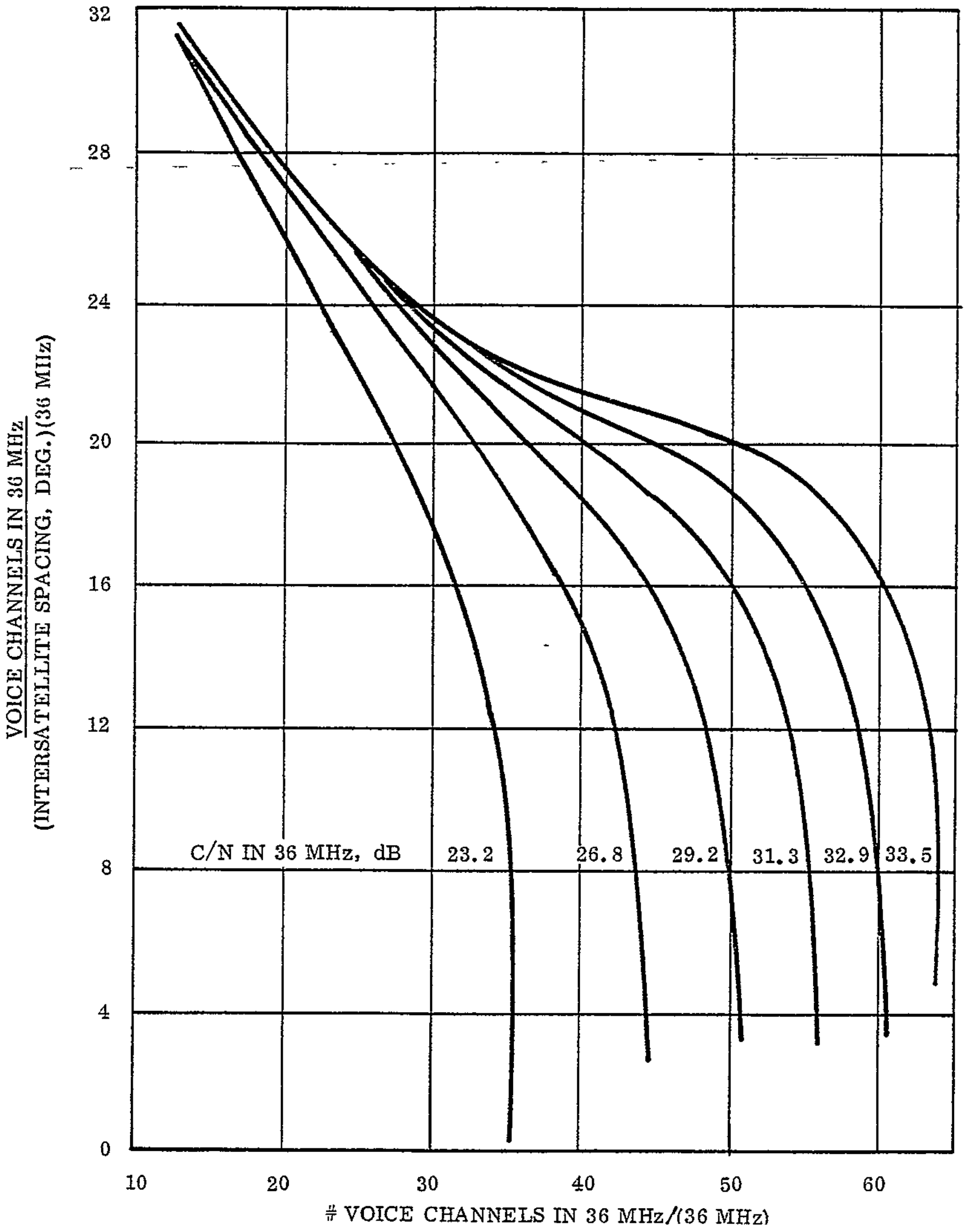


Figure 5-9. Orbit Spectrum Utilization (Voice), Rec: Dia. = 9.1m

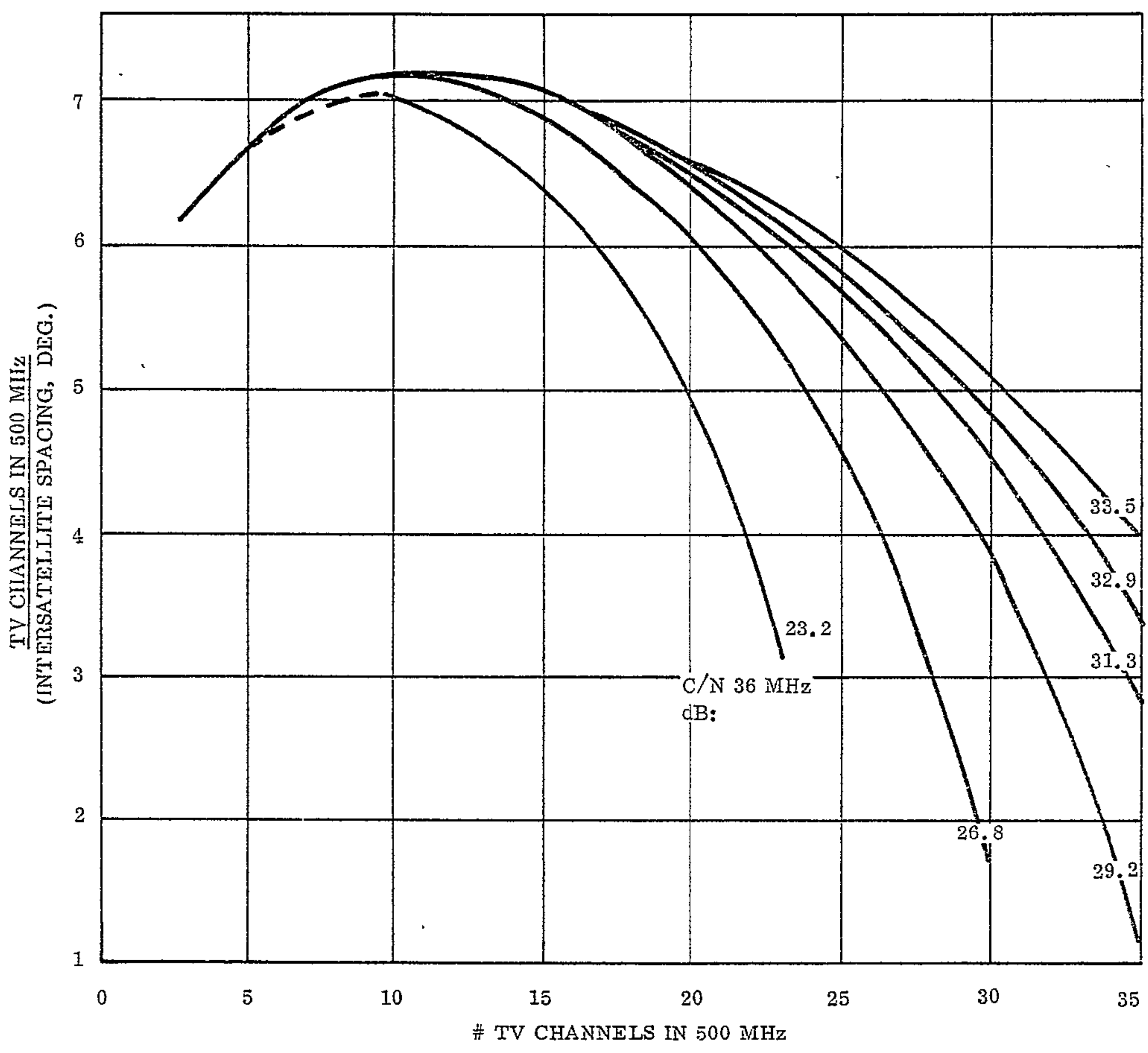


Figure 5-10. Orbit - Spectrum Utilization (FM-TV)
REC: DIA. = 9.1 m

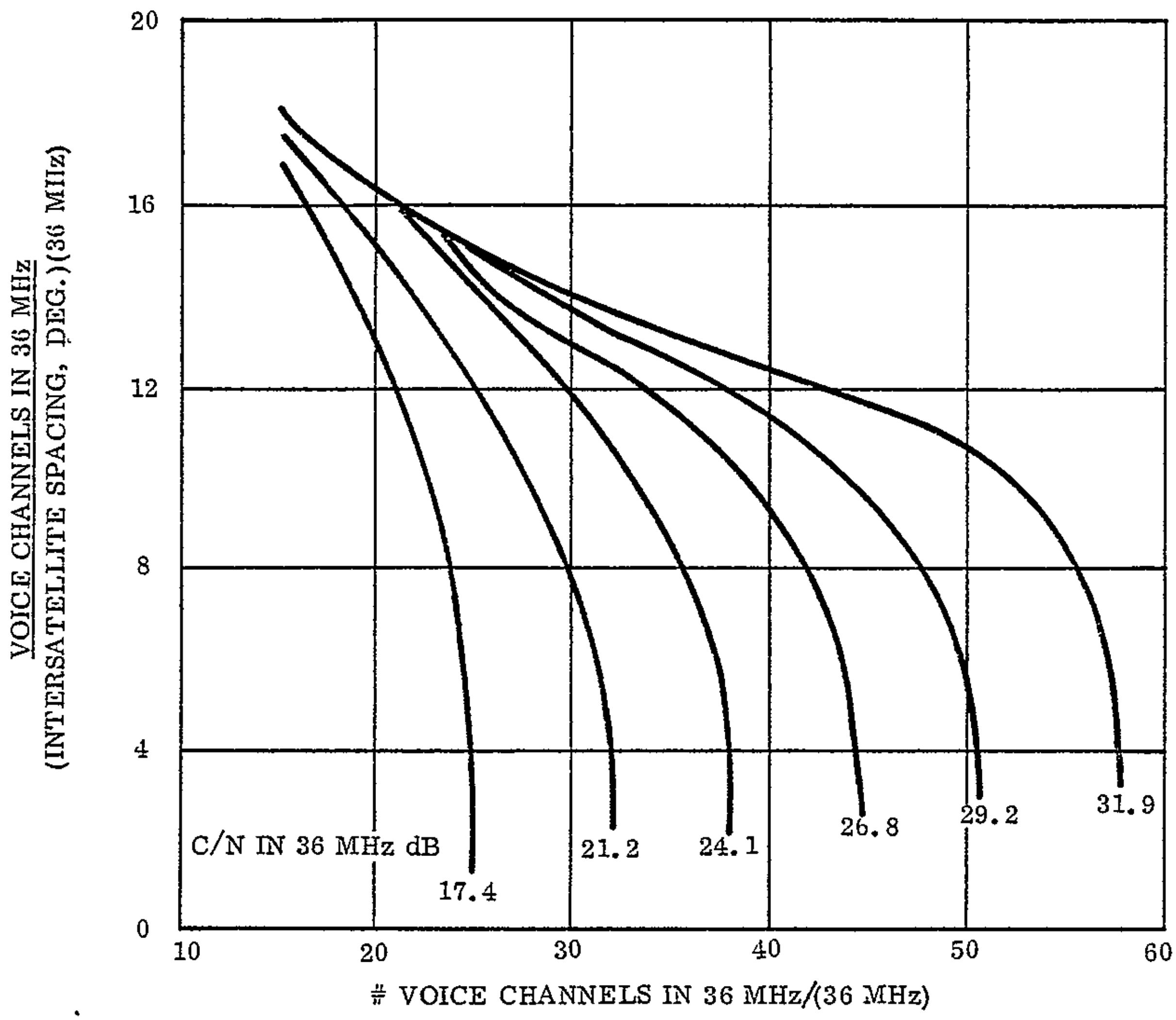


Figure 5-11. Orbit - Spectrum Utilization (Voice)
REC: DIA. = 4.6 m

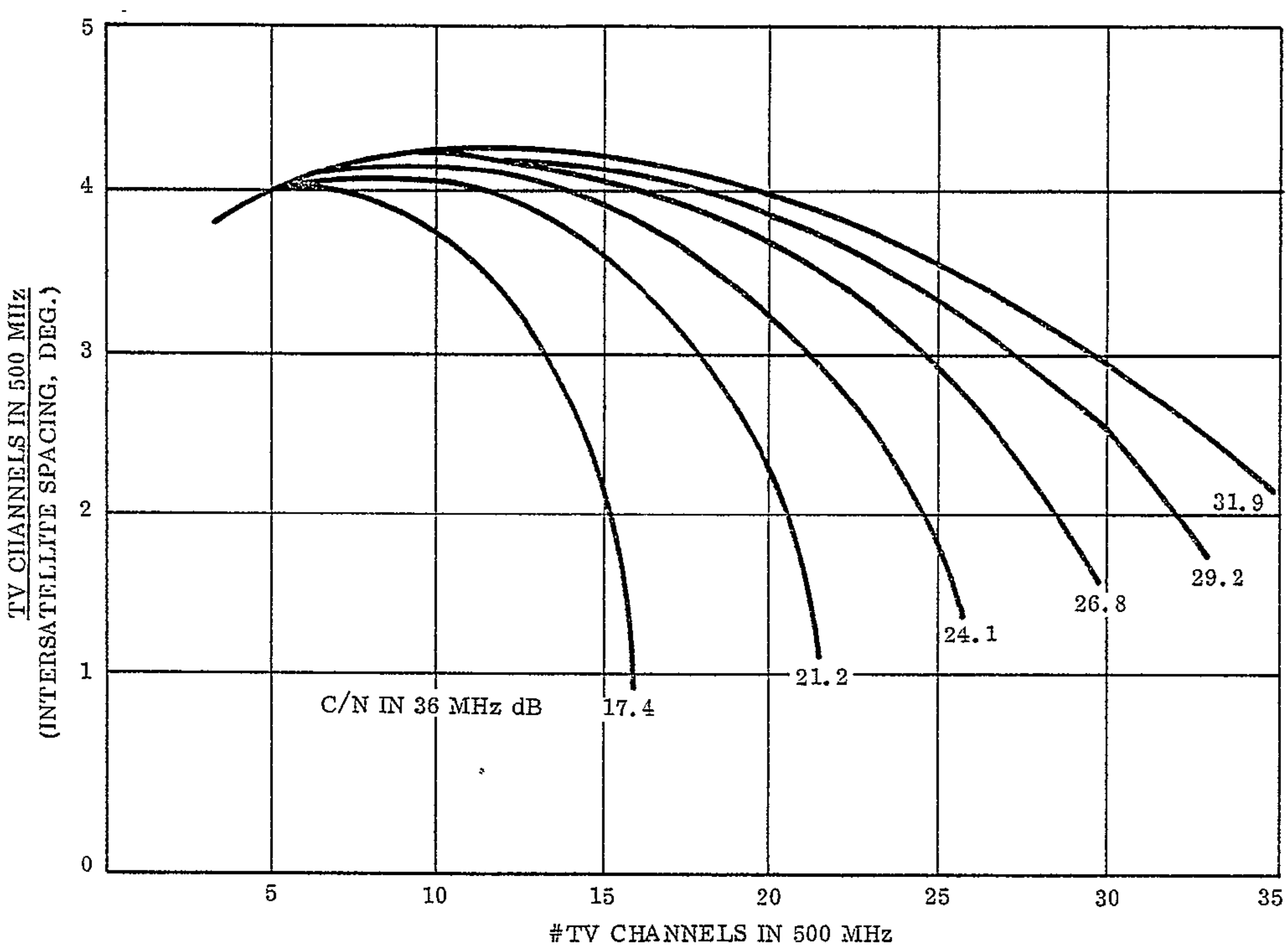


Figure 5-12. Orbit - Spectrum Utilization (FM-TV)

REC: DIA = 4. 6 m

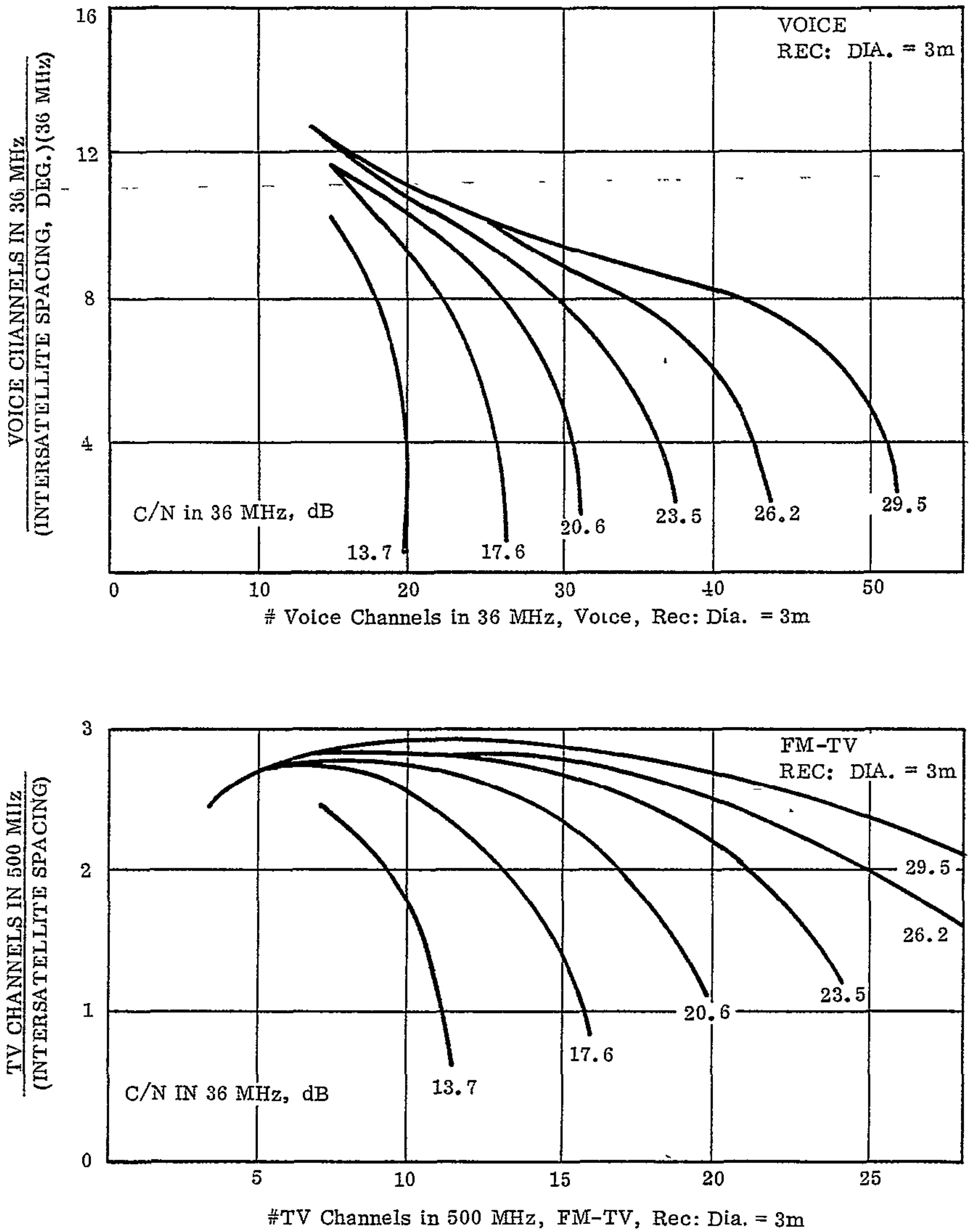


Figure 5-13. Orbit-Spectrum Utilization

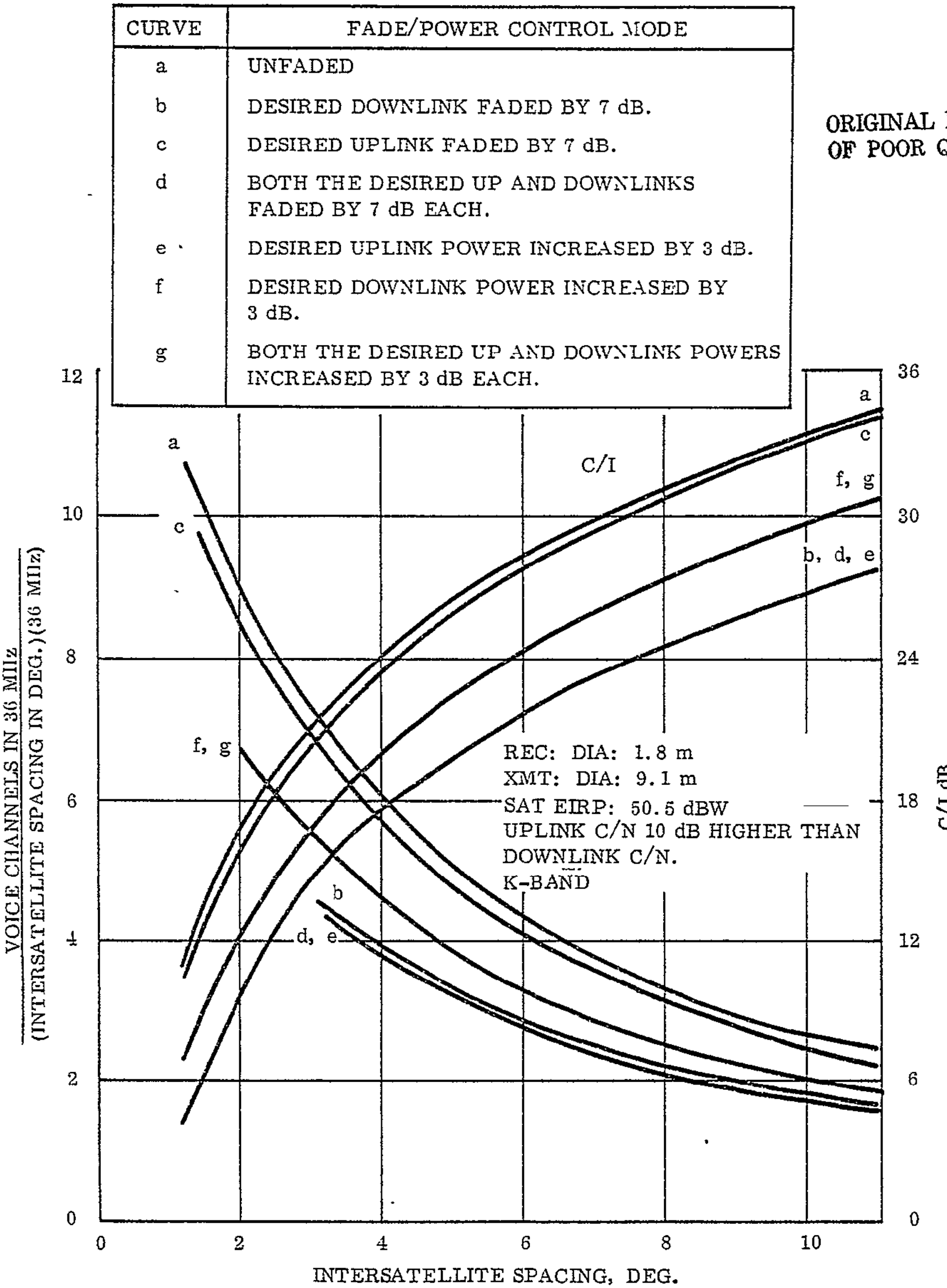


Figure 5-14. Effect of Fading/Power Control in Interference Environment on Voice Capacity - (Up and Downlink Fading)

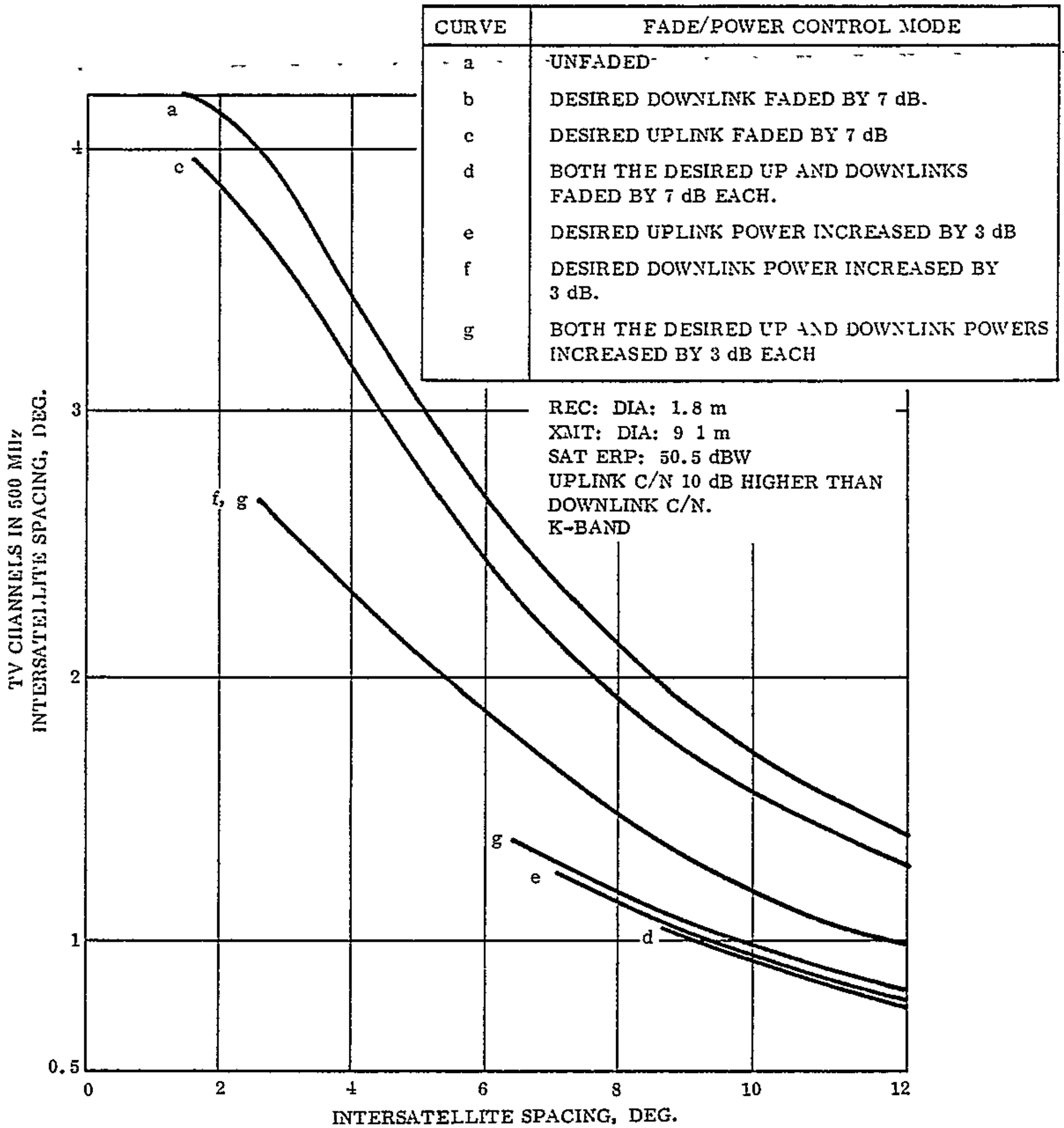


Figure 5-15. Effect of Fading/Power Control in Interference Environment on FM-TV Capacity - (Up and Downlink Fading)

CURVE	FADE/POWER CONTROL MODE
a	UNFADED
b	DESIRED DOWNLINK FADED BY 7 dB.
c	DESIRED UPLINK FADED BY 7 dB.
d	BOTH THE DESIRED UP AND DOWN LINKS FADED BY 7 dB EACH.
e	DESIRED UPLINK POWER INCREASED BY 3 dB.
f	DESIRED DOWNLINK POWER INCREASED BY 3 dB.
g	BOTH THE DESIRED UP AND DOWNLINK POWERS INCREASED BY 3 dB EACH.

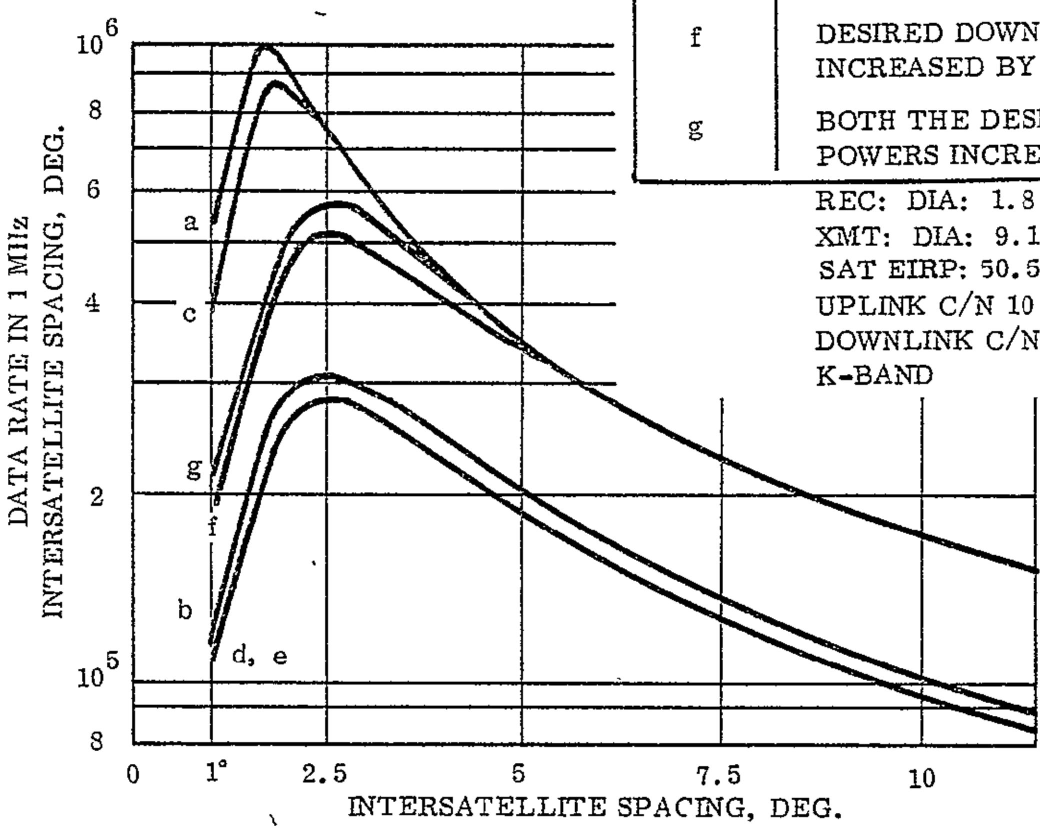


Figure 5-16. Effect of Fading/Power Control in Interference Environment on Data Capacity - (Up and Downlink Fading)

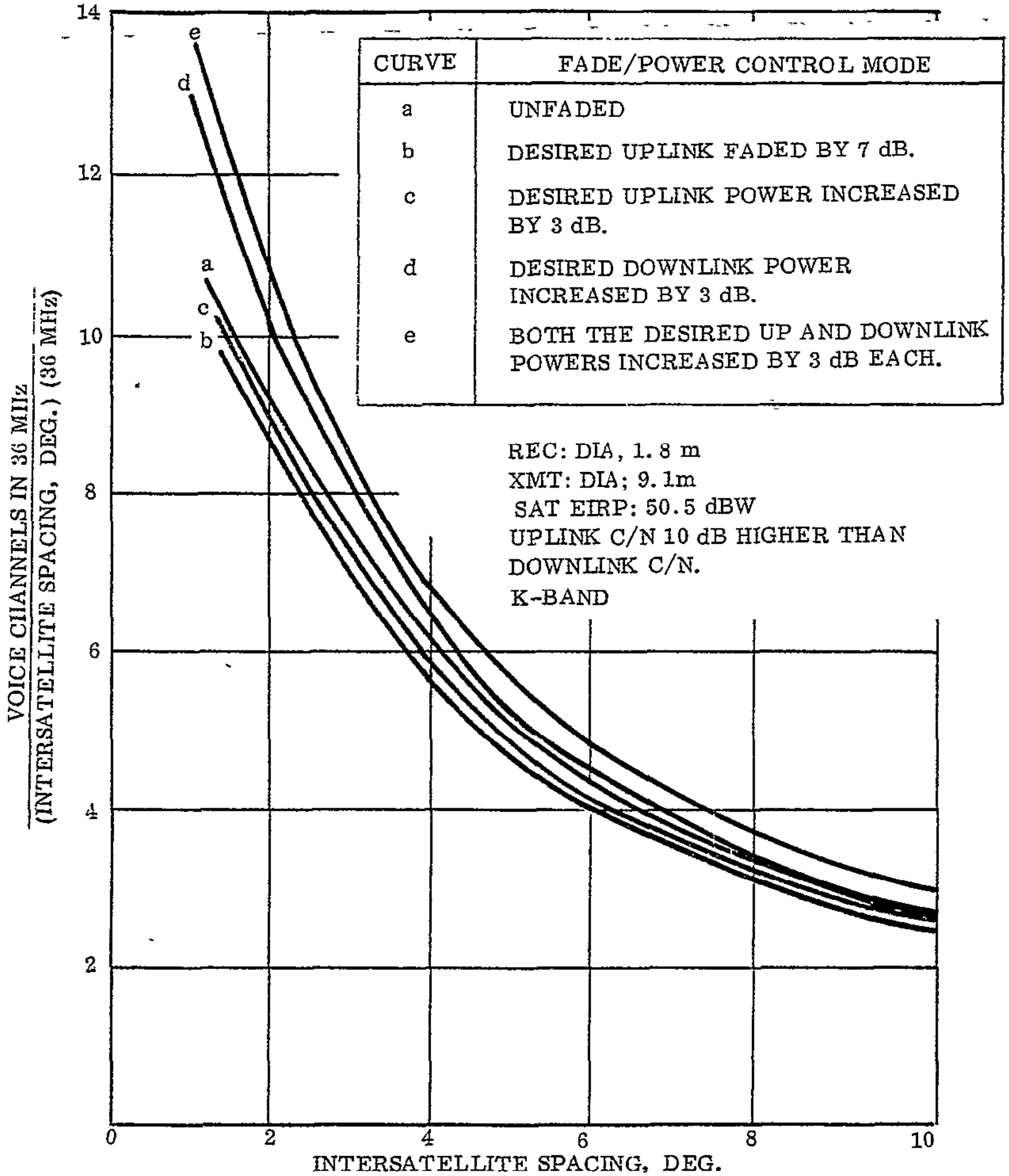


Figure 5-17. Effect of Fading/Power Control in Interference Environment on Voice Capacity - (Uplink Fading)

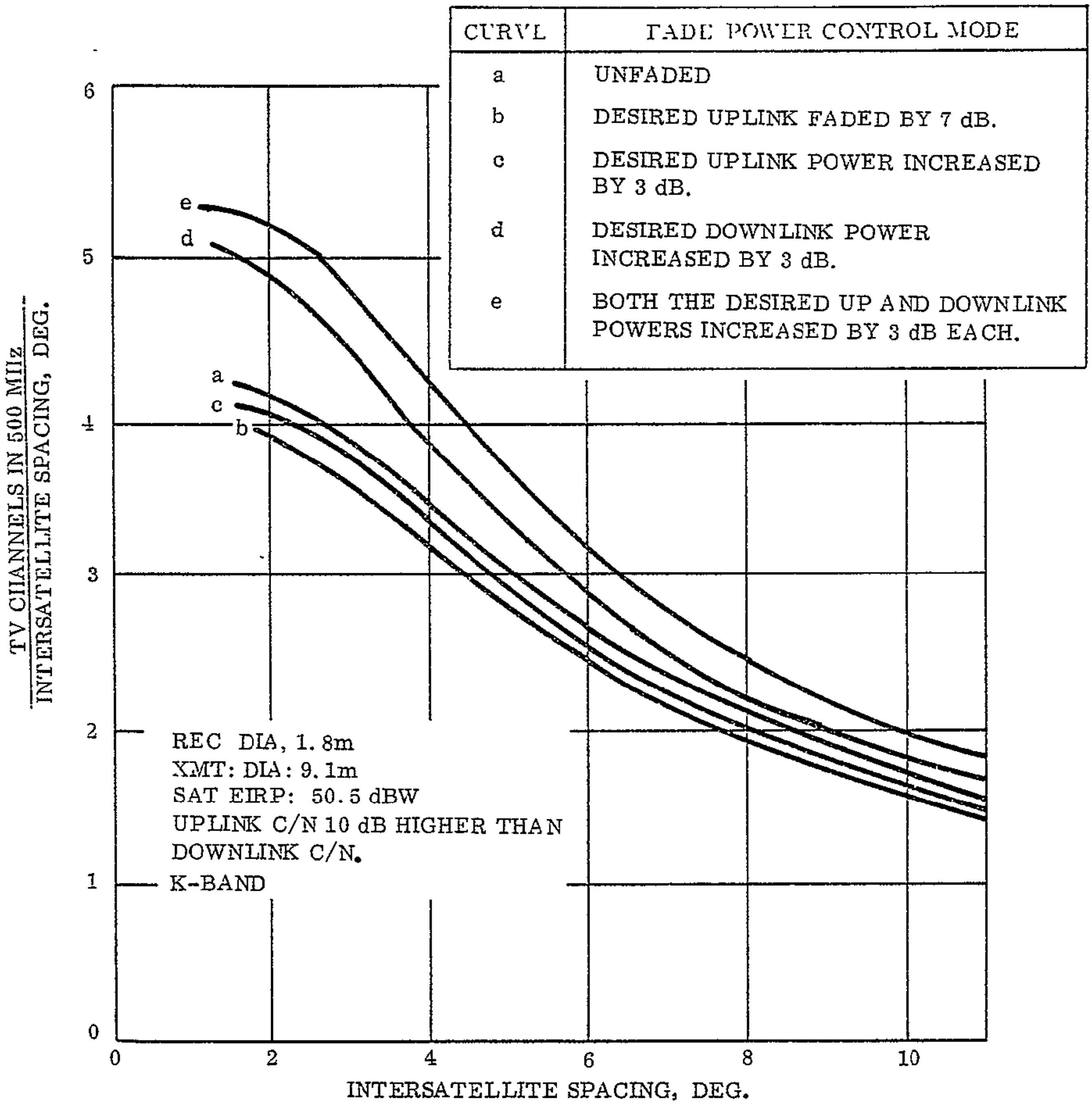


Figure 5-18. Effect of Fading/Power Control in Interference Environment on FM TV Capacity - (Uplink Fading)

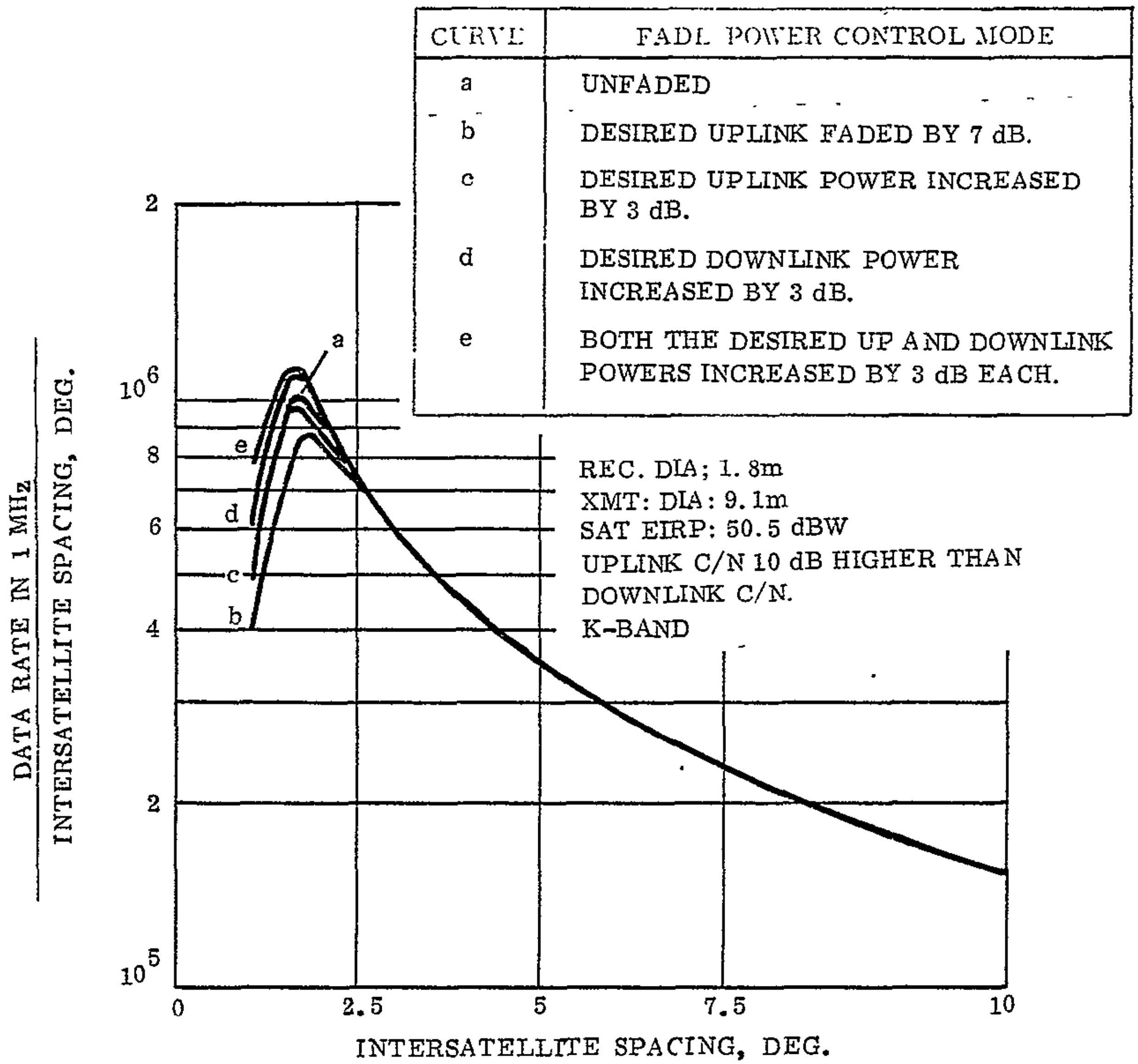


Figure 5-19. Effect of Fading/Power Control in Interference Environment on Data Capacity - (Uplink Fading).

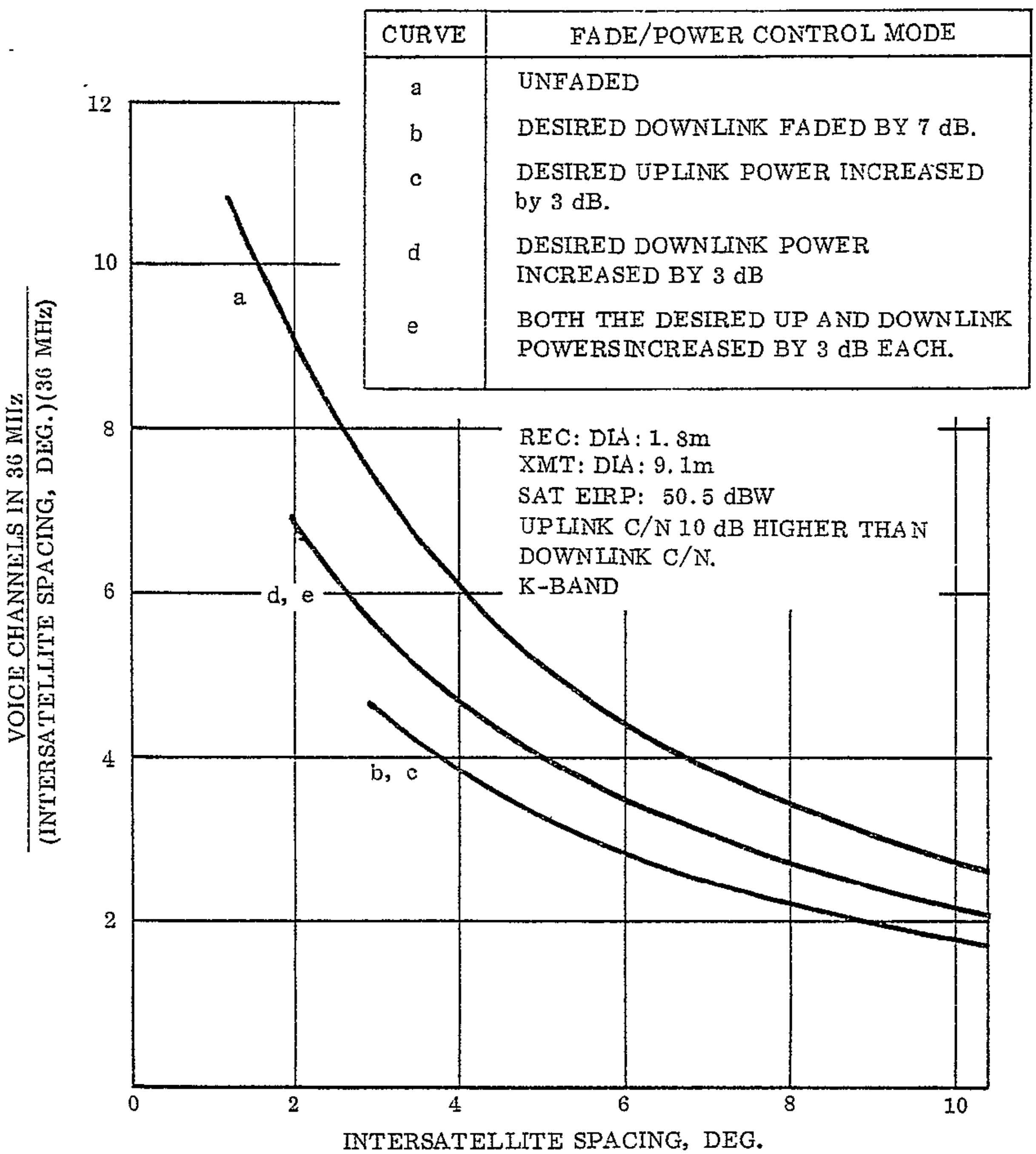


Figure 5-20. Effect of Fading/Power Control in Interference Environment on Voice Capacity - (Downlink Fading)

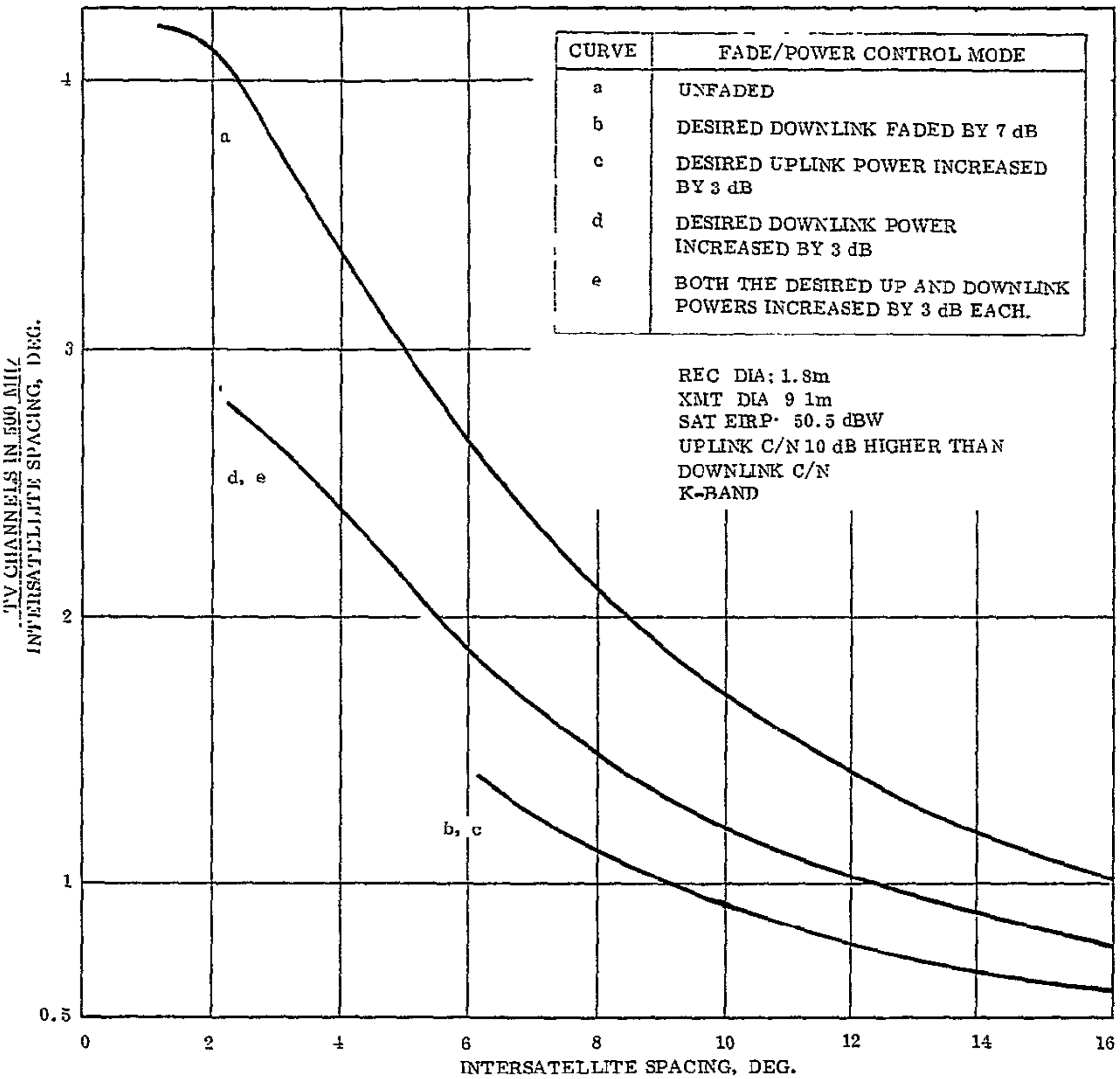


Figure 5-21. Effect of Fading/Power Control in Interference Environment on FM TV Capacity (Downlink Fading)

CURVE	FADE/POWER CONTROL MODE
a	UNFADED
b	DESIRED DOWNLINK FADED BY 7 dB.
c	DESIRED UPLINK POWER INCREASED BY 3 dB.
d	DESIRED DOWNLINK POWER INCREASED BY 3 dB.
e	BOTH THE DESIRED UP AND DOWNLINK POWERS INCREASED BY 3 dB EACH.

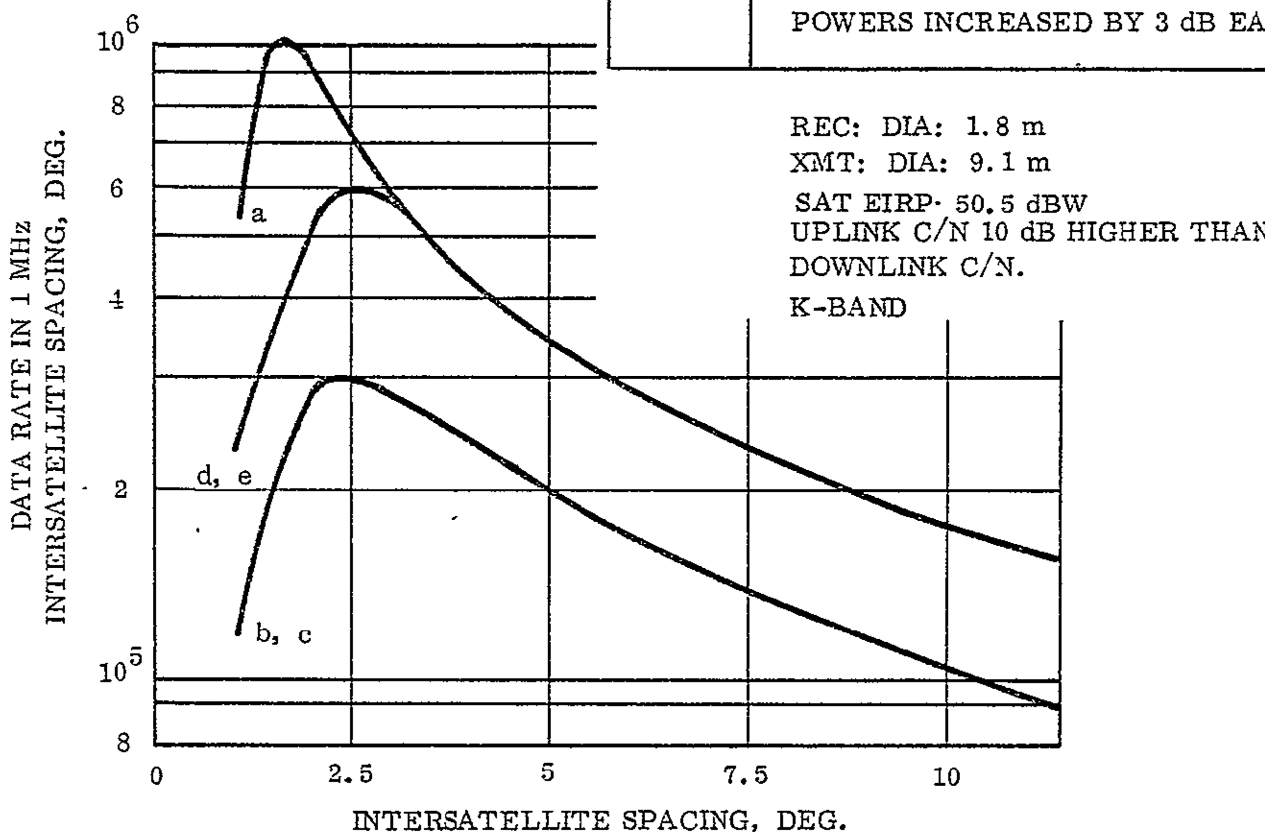


Figure 5-22. Effect of Fading/Power Control in Interference Environment on Data Capacity - (Downlink Fading)

B. FUTURE TECHNOLOGY

Future technology involving multiple satellite beams and Satellite Switched TDMA (SS/TDMA) is considered. The capacity is computed by using the methodology given in Appendix-6 and the results are presented in Figure 5-8. It is assumed that CONUS is covered by 105 spot beams which uniformly cover the geographical area. In terms of angular dimensions, since CONUS is approximately 6.8° from East to West and 3.5° from North to South, the angular area covered by one spot beam is 0.238 $(\text{degrees})^2$ which yields a half 3dB beamwidth of $(1/2\sqrt{.238}) = 0.25^{\circ}$. It is assumed that these beams are arranged in a 7 (N-S) by 15 (E-W) matrix and of these only fifteen (15) beams are copolarized and transmit cochannel carriers and hence present potential interference possibilities. These 15 beams are assumed to be symmetrically situated within the center of the geographical area in a 3 beam by 5 beam matrix with three beams in the N-S direction and five beams in the E-W direction. Various spot beams with the fifteen identified are shown in the insert in Figure 5-8. The capacity is computed for three receive antenna diameters of 1.8, 3, and 4.6 meters at K-band by assuming that the sum of the satellite EIRP and the gain of the receive antenna yields a C/No of 90 dB - Hz. This normalization reveals the effects of antenna sidelobes. The probability of error is kept constant at 10^{-4}. The indicated capacity can be enhanced by increasing C/No.

C. RF BAND AND POLARIZATION PLANS

Various RF band, polarization and satellite arrangements are possible. There are six such arrangements defined in Table 5-3(a). In Table 5-3(b) the polarization and frequency bands on adjacent satellites are shown for the six arrangements. Although there will be many satellites in the orbital arc, only the arrangement on three contiguous satellites is sufficient to identify the arrangement. The total RF band available is dependent on the frequency band: 500 MHZ is used in the figures for illustration. The frequency bands are shown by rectangles and the bands are either "full" or "split". The polarization is indicated by P_1 and P_2; and when polarization P_2 is used, the connotation is that it may be linear or circular but orthogonal to P_1.

In the first arrangement shown in Table 5-3(b) the band is split into two halves and the alternate halves are used on adjacent satellites. The predominant interference in this case is from the alternate satellite.

In the second arrangement in Table 5-3(b), the assigned band is split into two halves and both halves are used on each satellite. Also, both polarizations are used on each satellite and the manner in which they are used is such that adjacent satellites are orthogonally polarized on cochannels. In this case also, the predominant interference is between alternate satellites.

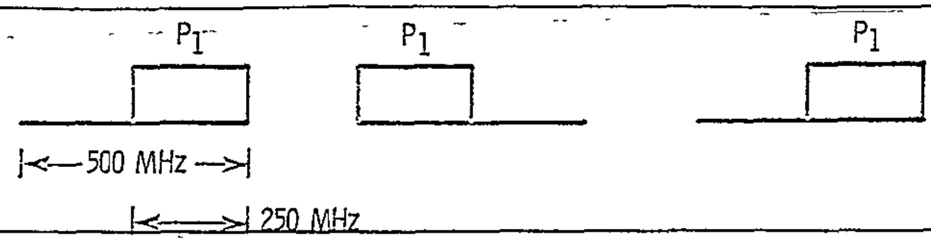
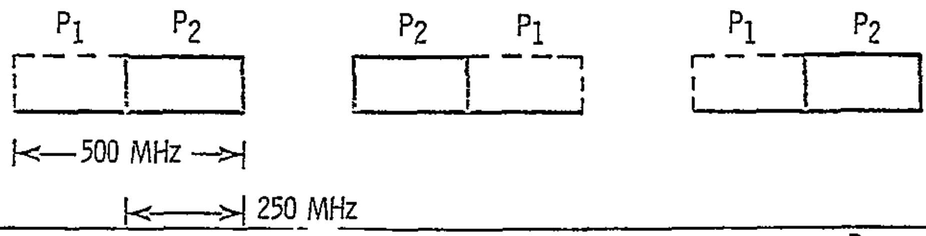
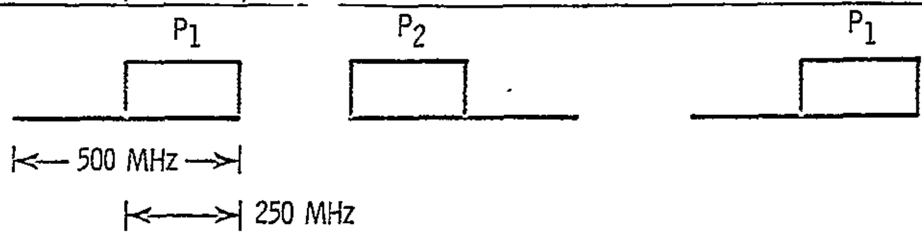
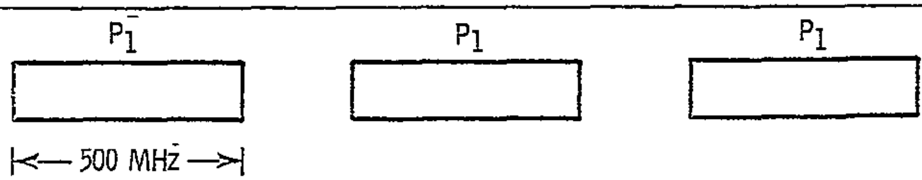
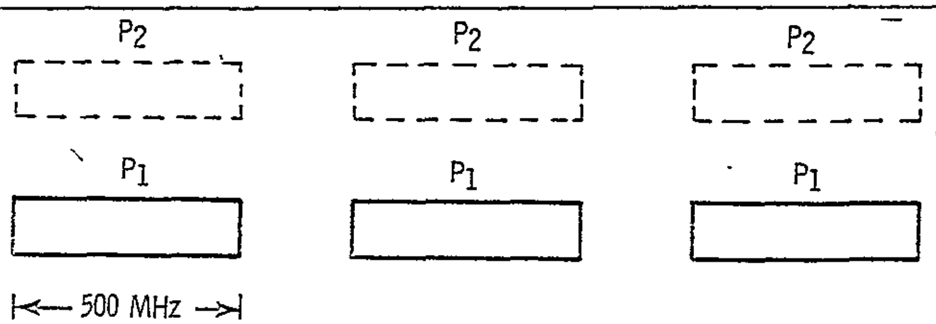
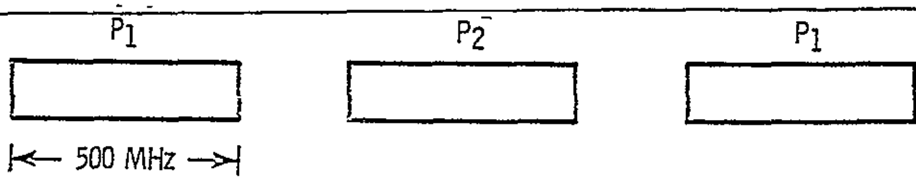
In the third arrangement in Table 5-3(b), alternate halves of split bands are used on adjacent satellites and the polarization is switched to its orthogonal counterpart on adjacent satellites. In this case also, the predominant interference is between alternate satellites.

Table 5-3 (a). RF Band, Polarization and Satellite Arrangements

Polarization and Satellite Arrangement / RF Band	Single Polarization on all Satellites	Dual Polarization on all Satellites	Orthogonal Single Polarization on Adjacent Satellites
Split Band	1	2	3
Full Band	4	5	6

Table 5-3 (b)

RF Band/Polarization Arrangement

Arrangement Number	RF Band/Polarization Arrangement
1	
2	
3	
4	
5	
6	

The fourth arrangement shown in Table 5-3(b) is a "full" band case and polarization is the same on each satellite. The predominant interference is between adjacent satellites.

The fifth arrangement in Table 5-3(b) is the full band case but both orthogonal polarizations are used on each satellite. This represents a case in which the frequency band is used twice. The predominant cochannel interference is between co-polarized bands on adjacent satellites.

The sixth arrangement in Table 5-3(b) is also a full band case in which polarization is alternated on adjacent satellites. The predominate interference is also between alternate satellites.

In all, six arrangements have been discussed. But so far as capacity per degree of arc is concerned, these six arrangements are really only two sets with set #1 consisting of arrangements 1, 3 and 4, and set #2 consisting of arrangements 2, 5 & 6. Set #2 gives double the capacity of Set #1.

D. ORBIT-SPECTRUM UTILIZATION

In an effort to reveal influential factors. the orbit-spectrum utilization is studied for FDM-FM voice and FMTV for some representative antenna diameters at K-band. The results are described in Figures 5-9, 11, 13 for FDM-FM voice. In these figures, the ordinate is

$$\text{Ordinate} = \frac{\text{Voice channels in specified bandwidth}}{\underset{\text{degrees}}{\text{(Intersatellite Spacing)}}\ \text{(Specified bandwidth, MHz)}}$$

which is the same as the first entry in Table 5-2. For these curves, the abcissa is

$$\text{abcissa} = \frac{\text{Voice channels in specified bandwidth}}{\text{(Specified bandwidth, MHz)}}$$

Each figure corresponds to a particular diameter and the C/N ratio for each curve in the figure is marked. As one traverses a particular curve from bottom to top, the inter-satellite spacing (although it is not explicitly shown in the figure) decreases. Near the abcissa, the curves corresponding to various C/N ratios approach parallelism. Near the abcissa the intersatellite spacing increases and, therefore, for the fixed voice channel quality the interference noise is less than thermal noise. Along the abcissa the channel noise is completely thermal because a zero value of the ordinate implies that the intersatellite spacing is infinite and consequently the interference noise is vanishingly small. Although the curves for various C/N ratios separate as they approach the horizontal axis, they merge at the top and tend to be indistinguishable; the reason for this is that in this region the intersatellite spacing is small and hence the carrier/interference ratio is small and the carrier to thermal noise is irrelevant; the noise in the channel is almost all interference noise and the utilization is governed only by the interference transfer behaviour. The curves terminate in the top lefthand edge at a point when the interference and thermal noise at the receiver input combine to yield a net carrier-to-thermal plus interference noise ratio which is equal to the set threshold (10 db). If FM operation below 10 db threshold is

permitted, the curves will continue their upward trend, merging as one curve until the curves become asymptotic to the vertical axis. This behaviour indicates that as the abcissa (voice channels in specified BW/Specified BW, MHZ) approaches zero the ordinate (voice channels in Specified BW/(Intersatellite spacing degrees) (Specified BW, MHZ)) approaches infinity. When the value of the variable along the abcissa approaches zero, a very large carrier deviation or bandwidth is being used for very small or vanishingly small numbers of channels. When the value of the variable along the ordinate approaches infinity, the intersatellite spacing approaches zero and as a consequence the value of the abcissa (or the number of channels per MHZ) approaches zero in order to keep the interference plus thermal noise at a constant level.

These curves show that as long as the C/N ratio keeps the system above threshold in the presence of interference, higher C/N ratios lose effectiveness and do not allow improved orbit utilization. The spectrum utilization can be traded with orbit utilization, however, orbit utilization cannot be enhanced by making more use of very low noise receivers.

Figures 5-10, 12, 13 depict the orbit spectrum utilization behaviour for FM-TV for representative antenna sizes at Ku-Band. In these figures, the variable represented along the ordinate is

$$\text{Ordinate} = \frac{\text{TV channels in allocated bandwidth}}{\text{Intersatellite Spacing}}$$

and the variable represented along the abcissa is

abcissa = TV channels in allocated bandwidth.

In order to highlight the behaviour, the effect of interference has been increased by assuming that the receiver transfer improvement factor is 6 db lower (i.e. in equation 74 Appendix-6, K = 0 db); therefore no conclusion about capacity can be drawn from these figures. In this case the C/N ratio is constant for each curve; while one traverses a particular curve from the bottom righthand end towards the top left the interference noise increases so that the resulting net quality due to the baseband effects of thermal and interference noise remains constant at a preset value. Increasing the C/N ratio increases orbit utilization but soon a point of diminishing returns is reached when proportionately larger amounts of interference (compared with thermal noise) make up the preset baseband quality. Increasing C/N buys comparatively little in orbit utilization. The orbit and spectrum utilization curves exhibit peaks beyond which any decrease in spectral utilization causes a decrease in orbit utilization also and operation in this region is not advantageous. The curves stop when threshold is reached.

E. EFFECTS OF FADING AND COMBATTING MEASURES

When a communications satellite system is operating in the presence of other interfering communications satellite systems, fading has to be looked at in an unconventional way. In such a situation, harmful fading can take place when the desired communications satellite link fades while the links of the interfering satellite communications systems do

not fade. In this case, the desired link suffers in two ways: the carrier/noise ratio of the desired system degrades, and the carrier/interference ratio degrades. In other situations both the desired link and the interference fade together in which case the system thermal noise increases vis a vis the interference. So far as fading is concerned, the following possibilities exist:

(i) The desired uplink fades

(ii) The desired downlink fades

(iii) Both the desired up and downlinks fade

In these three modes of fading, the worst that can happen is that the interfering links do not fade. Capacity degradation in these fade modes are shown for voice, TV and Data in Figures 5-14 through 5-22.

Since the satellite transponder normally has constant gain, any uplink fade will automatically cause a downlink fade, the extent of which will depend upon the operating point of the transponder. The results depicted in these figures assumes that AGC has been employed in the satellite by means of which the effect of uplink fade on the downlink fade is eliminated. The reduction in capacity due to fading can be recovered by "power control" and the following three power control strategies are examined.

1. Uplink power control (via earth station HPA)

2. Downlink power control (via satellite transmitter)

3. Both uplink and downlink power control

When considering the effects of fading, it is assumed that 7dB fades occur and while counteracting the effects of fading it is assumed that the power can be increased by 3 db, i. e., uplink power can be increased by 3dB, the downlink power can be increased by 3 db or each up and downlink power can be increased by 3 dB.

The following inferences can be made from Figure 5-14 thru 5-22. Since AGC is assumed and the limiting link is the downlink, uplink fading has a smaller effect on capacity in comparison with equal amount of downlink fading. By the same token, uplink power control is less effective in combatting the effects of fading since during fading the interference also increases, if a system is required to be operative in the presence of fading without the use of power control the intersatellite spacing has to be kept larger to reduce interference before fading. However, this technique is wasteful because fading is an occasional phenomena and in order to ameliorate its effects, loss in orbital capacity is incurred. The downlink fading has a significantly larger effect on capacity and at the same time can be compensated by downlink power control.

When both up and downlinks fade (highly unlikely) the effects are comparable to downlink fading.

The effect of fading and power control on FM-TV is similar to that on FDM-FM voice. That is, when the downlink is limiting, uplink fading causes an insignificant loss in capacity. At the same time uplink power control is comparatively ineffective in curing the loss of capacity due to fading. Downlink fading is more serious but at the same time downlink power control is more effective in recouping the capacity lost by fading. When only the uplink fades, using downlink power control as the remedial measure might even cause an enhancement in the capacity because a 3dB increase in the downlink power has more effect than a 3dB increase in the uplink power. Since it is generally true that the downlink will be the limiting link, downlink power control is more effective and should be given consideration in future satellite implementations.

The effect of fading and power control in the case of data is shown in Figures 5-16, 19, 22. The same ground rules apply as in the FDM-FM and FM-TV cases. Again, the downlink is the dominating link and therefore the uplink power control is ineffective in recouping capacity lost due to fading. Generally, downlink power control is effective except in the special circumstance when the uplink is the limiting link. Again, in order to make fading less harmful with no power control the intersatellite spacing should be kept large; but this, for same reasons as before, is not a prudent artifice.

F. FACTORS AFFECTING CAPACITY

Various factors that affect orbital capacity are:

- Antenna sidelobe characteristics
- Modulation
- Propagation effects
- Earth station power and noise performance

Capacity is limited by the interference received at the Earth terminal receiver input. The amount of interference depends upon the sidelobes of various antennas involved in communication. These antennas are satellite receive and transmit antennas and the earth terminal transmit and receive antennas. Increased amount of interference costs capacity whether the communications service is FDM-FM voice, FM-TV or Data Communication. Sidelobe levels in a practical situation depend upon the type of the antenna. In the case of typical paraboloidal antennas radiation characteristics are determined by the nature of aperture illumination function and by blockage. The illumination of the antenna aperture by the feed subsystem can be shaped to yield low sidelobe radiation and thereby result in enhanced capacity. In general, larger earth terminal antennas allow smaller intersatellite spacing and vice versa. The orbital spacing and hence the overall orbital capacity when the satellites make use of the same spectrum is related to the earth station antenna gain. Progressively narrower intersatellite spacing decreases as frequency increases for the same antenna diameter and vice versa. Small antennas are certainly attractive at K-band. Capacity computations reveal that it does not make much difference when the FCC Sidelobe pattern is modified such that the Sidelobe radiation remains constant after the Sidelobes are down 60 db from peak (X = 60 dB). But for X=40dB the capacity suffers

slightly only for smaller receive antennas. Needless to say, the capacity improves if the close in sidelobe radiation can be suppressed. When the satellite antenna gain is increased, the capacity increases and becomes insensitive to the sidelobe radiation characteristics of the earth terminal antennas.* High gain antennas on board the satellites can be used to reduce the intersatellite spacing and/or can be used to offset the effect of larger sidelobes of earth terminal antennas and hence reduce antenna costs. While stationkeeping tolerances have not been taken into consideration, certain inferences about its effects can still be drawn. Because high orbit utilization is achieved at small intersatellite spacing it is natural to expect that satellite stationkeeping tolerances will have an important effect on capacity. Stationkeeping tolerances will be important for larger antennas and higher operating frequencies.

Modulation and modulation parameters are certainly pertinent in affecting the capacity. In the case of FDM-FM voice when the satellite allocated bandwidth is channelized (like the 36 MHz wide sections assumed in the computations) the orbit utilization increases as the satellite spacing is narrowed (until system threshold is attained). Highest utilization of the orbit is achieved at satellite spacings of 1-2°. In the case of FDM-FM the parameters which affect orbital efficiency is (voice channels in a specified BW)/(Specified BW) and this can be directly traded for orbit utilization. Reducing this parameter or the number of channels/MHz allows a reduction in intersatellite spacing. No preferential treatment should be granted to a particular communications satellite in the orbit. The communications capacity of a particular communications satellite system can be enhanced by increasing the above parameter but at the expense of larger intersatellite spacing and as a consequence, the overall orbital capacity will be degraded.

In the case of FM-TV operation is not under fixed bandwidth conditions as in the case for FDM-FM voice. Here for a fixed baseband quality the carrier deviation is increased to provide increased resistance to interference from other satellite systems. With such an operation the orbit utilization increases as the intersatellite spacing is reduced (until threshold is attained). An appropriate parameter affecting the orbital efficiency is (TV channels in allocated BW) and this can be traded for orbit utilization in the same manner as in the case of FDM-FM voice.

In the case of 4-phase PSK data the capacity descriptor is:

$$\frac{\text{Data rate in Specified BW}}{\text{(Intersatellite Spacing) (Specified BW)}}$$

Variation of this parameter as a function of intersatellite spacing exhibits a peak. Below this peak on the left (smaller intersatellite spacing) there is no excess satellite power and below this peak on the right (larger intersatellite spacing) there is excess satellite power. Exactly the reverse is true so far as bandwidth is concerned. This peak is sharp when power is low and interference is large (see Figures 5-16, 19, 22).

* Compare Tables 5-4, 9, 12, 15 with 5-5, 10, 13, 16 respectively

Precipitation and propagation have at least * a dual effect on capacity. Carrier power reduces capacity due to fading and if the desired link fades and the interfacing links do not, the interference power rises in relation to the desired carrier power. Both these effects limit capacity. Two remedial measures involving keeping the intersatellite spacing larger or implementing means for downlink power control **

Capacity is also a direct function of the Earth Station performance parameters, the most important of which are the antenna size, and the system noise temperature. These affect capacity in the usual manner but with the additional influence that interference will be less with a larger antenna.

G. RECOMMENDATIONS

As a result of the Study the following recommendations can be made:

- Smaller intersatellite spacings of around 2^{o} can be used at Ku band
- Sidelobe radiation characteristics of the satellite antenna can and should be improved.
- The close in sidelobe radiation characteristics of the ground terminal antennas can be improved.
- For a fixed baseband quality constraint in the case of FDM-FM voice and FM-TV baseband noise may be predominantly due to interference. This might require additional experimentation to assess the subjective effects of increased baseband interference noise on Voice and TV.
- The effective radiated powers per MHz of communications satellite systems in the orbit should not be significantly different.
- Means of implementing downlink power control should be investigated in future satellite designs.

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* Depolarization and Scattering

** While not considered herein, an alternative to power control is earth station antenna systems diversity.

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Table 5-4

K-Band Broadcast Communication Capacity

TIME ZONE * Xmt Antenna dia = 9 1m

ΔΘ	Gain Model Case	VOICE Rec. Dia. 0.6	1.8	3	4.6	TV 0.6	1.8	3	4.6	DATA 0.6	1.8	3
0.5	1	-	-	-	-	-	-	-	-	.12E5	.38E6	.11E7
	2	-	-	-	-	-	-	-	-	.1E5	.35E6	.1E7
	3	-	-	-	-	-	-	-	-	.12E5	.38E6	.11E7
1	1	-	17.6	23.8	30.1	-	7.7	11.6	15.8	.35E6	.167E7	.167E7
	2	-	16	19.2	21	-	6.7	8.7	9.8	.33E6	.167E7	.167E7
	3	-	17.6	23.8	30.1	-	7.7	11.6	15.8	.35E6	.11E7	.167E7
2	1	7.5	14.5	20.2	30	3.1	7.6	10.7	13.6	833E6	.833E6	.833E6
	2	7.4	11.9	13	13.6	3	5.8	6.7	7	.833E6	.833E6	.833E6
	3	7.6	14.5	20.2	30	3.1	7.6	10.7	13.5	.833E6	.833E6	833E6
3	1	6.6	12.9	19.7	25.6	3	7	9.4	11.4	.56E6	.56E6	.56E6
	2	6.4	9.5	10.5	10.5	2.9	5	5.4	5.6	.56E6	56E6	.56E6
	3	6.6	13	19.7	25.5	3.1	7	9.4	11.3	.56E6	.56E6	.56E6
4	1	5.9	11.7	16.9	19.6	3	6.3	8.2	9.6	.42E6	.42E6	.42E6
	2	5.6	8	8.6	8.8	2 8	4.3	4.6	4.7	.42E6	.42E6	.42E6
	3	5.9	11.7	.17	19.5	3	6.4	8.2	9.5	.42E6	.42E6	.42E6
5	1	5.2	10.4	13.9	15.7	2.8	5.7	7.2	8.2	33E6	.33E6	.33E6
	2	5	7	7.4	7.5	2.6	3.8	4	4	.33E6	.33E6	.33E6
	3	5.2	10.5	13.9	15.7	2.9	5.8	7.2	8.2	.33E6	.33E6	.33E6

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 300 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- ΔΘ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold

* Easternmost

Table 5-5

K-Band Broadcast Communication Capacity   Xmt Antenna dia = 9.1m

TIME ZONE, SHARP SATELLITE BEAM

Δθ	Gain Model Case	VOICE				TV				DATA		
		Rec. Dia. 0.6	1.8	3	4.6	0.6	1.8	3	4.6	0.6	1.8	3
.5	4	51.4	104	139	157	28	57.2	71.9	83	.33E7	.33E7	.33E7
	5	51.4	104	139	157	28	57.2	71.9	83	.33E7	.33E7	.33E7
	6	51.4	104	139	157	28	57.2	71.9	83	.33E7	.33E7	.33E7
1	4	29.4	56.2	70.4	79	17	32.3	39.4	44.4	.167E7	.167E7	.167E7
	5	29.4	56.2	70.4	79	17	32.3	39.4	44.4	.167E7	.167E7	.167E7
	6	29.4	56.2	70.4	79	17	32.3	39.4	44.4	.167E7	.167E7	.167E7
2	4	16	29	35.3	39.5	9.8	17.6	21	23.2	.83E6	.83E6	.83E6
	5	16	29	35.3	39.5	9.8	17.6	21	23.2	.83E6	.83E6	.83E6
	6	16	29	35.3	39.5	9.8	17.6	21	23.2	.83E6	.83E6	.83E6
3	4	11.1	19.5	23.6	26.4	6.9	12.2	14.4	15.8	.56E6	.56E6	.56E6
	5	11.1	19.5	23.6	26.4	6.9	12.2	14.4	15.8	.56E6	.56E6	.56E6
	6	11.1	19.5	23.6	26.4	6.9	12.2	14.4	15.8	.56E6	.56E6	.56E6
4	4	8.5	14.7	17.7	19.8	5.4	9.4	10.9	12	.42E6	.42E6	.42E6
	5	8.5	14.7	17.7	19.8	5.4	9.4	10.9	12	.42E6	.42E6	.42E6
	6	8.5	14.7	17.7	19.8	5.4	9.4	10.9	12	.42E6	.42E6	.42E6
5	4	6.8	11.8	14.2	15.8	4.4	7.6	8.8	9.6	.33E6	.33E6	.33E6
	5	6.8	11.8	14.2	15.8	4.4	7.6	8.8	9.6	.33E6	.33E6	.33E6
	6	6.8	11.8	14.2	15.8	4.4	7.6	8.8	9.6	.33E6	.33E6	.33E6

- Voice - The numbers represent (voice channels per MHZ/Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/Intersatellite spacing, deg)
- Δ θ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold

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Table 5-6

K-Band Broadcast Communication Capacity

ALASKA — Xmt Antenna dia = 9 1 m

Δθ	Gain Model Case	VOICE Rec. Dia. 0.6	VOICE 1.8	VOICE 3	VOICE 4.6	TV 0.6	TV 1.8	TV 3	TV 4.6	DATA 0.6	DATA 1.8	DATA 3
0.5	1	-	-	-	-	-	-	-	-	.29	.3E2	.1E3
	2	-	-	-	-	-	-	-	-	.27	.27E2	.9E2
	3	-	-	-	-	-	-	-	-	.29	.3E2	.1E3
1	1	-	-	14.5	18.3	-	-	5.8	8 1	.48E3	.14E7	.167E7
	2	-	-	12.6	14.2	-	-	4.7	5.6	.44E3	.1E7	.167E7
	3	-	-	14.5	18.2	-	-	5.8	8.1	.48E3	.14E7	.167E7
2	1	-	8.9	12	15	-	3.95	5.9	8	.32E5	.83E6	.83E6
	2	-	7.8	9.1	9.6	-	3.2	4.	4.4	.32E5	.83E6	.83E6
	3	-	8.9	12	14.9	-	3.95	5.9	7.9	.35E5	.83E6	83E6
3	1	-	7.8	10.4	13.4	-	3.9	5.6	7.3	.1E6	.56E6	.56E6
	2	-	6.4	7.1	7.4	-	2.9	3.4	3.6	.1E6	.56E6	.56E6
	3	-	7.8	10.4	13.3	-	3.9	5.6	7.2	.1E6	.56E6	.56E6
4	1	3.5	6.7	9.15	11.8	-	3.6	5 1	6.5	16E6	.42E6	.42E6
	2	3.4	5.5	6	6.2	-	2.6	3	3.1	.15E6	.42E6	.42E6
	3	3.5	6.7	9.15	11.7	-	3.6	5.1	6.4	.16E6	.42E6	.42E6
5	1	3.2	6.1	8.2	10.5	1.44	3.5	4.7	5.9	.2E6	.33E6	.33E6
	2	3.1	4.8	5	5.2	1.4	2.4	2.6	2.7	.18E6	.33E6	.33E6
	3	3.2	6.1	8.2	10.5	1.5	3.5	4.7	5.8	.2E6	.33E6	.33E6

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- Δθ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold

Table 5-7

K-Band Broadcast Communication Capacity

HAWAII Xmt Antenna dia=9.1m

Δθ	Gain Model Case	VOICE				TV				DATA		
		Rec. Dia. 0.6	1.8	3	4.6	0.6	1.8	3	4.6	0.6	1.8	3
0.5	1	-	-	-	-	-	-	-	-	.37	.3E2	1E2
	2	-	-	-	-	-	-	-	-	.35	.28E2	.9E2
	3	-	-	-	-	-	-	-	-	.37	.3E2	1E2
1	1	-	-	14.9	18.8	-	-	6	8.4	.76E3	.167E7	.167E7
	2	-	-	13	14.7	-	-	4.9	5.9	.7E3	.13E7	.167E7
	3	-	-	14.9	18.8	-	-	6	8.4	.76E3	.167E7	.167E7
2	1	-	9.3	12.4	15.6	-	4.2	6.2	8.3	.48E5	.83E6	.83E6
	2	-	8.1	9.4	10	-	3.4	4.2	4.6	.43E5	.83E6	.83E6
	3	-	9.3	12.4	15.5	-	4.2	6.2	8.2	.48E5	.83E6	.83E6
3	1	-	8.1	10.9	14	-	4.1	5.9	7.6	.14E6	.56E6	.56E6
	2	-	6.7	7.4	7.7	-	3.1	3.6	3.8	.13E6	.56E6	.56E6
	3	-	8.1	10.8	13.9	-	4.1	5.9	7.6	.15E6	.56E6	.56E6
4	1	3.7	7.1	9.7	12.6	-	3.9	5.5	6.9	.2E6	.42E6	.42E6
	2	3.6	5.7	6.2	6.3	-	2.8	3.1	3.2	.19E6	.42E6	.42E6
	3	3.8	7.1	9.7	12.4	-	3.9	5.5	6.8	.2E6	.42E6	.42E6
5	1	3.4	6.4	8.6	11	1.6	3.7	5	6.1	.24E6	.33E6	.33E6
	2	3.2	4.9	5.3	5.4	1.5	2.5	2.7	2.8	.2E6	.33E6	.33E6
	3	3.4	6.4	8.6	10.9	1.6	3.7	5	6.1	.24E6	.33E6	.33E6

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- Δθ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold

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Table 5-8
S-Band Broadcast Communication Capacity
CONUS

Xmt Antenna dia = 9 1 m

Δ Θ	Geom Model Case	VOICE Rec Dia 0.6	1.8	3	4.6	TV 0.6	1.8	3	4.6	DATA 0.6	1.8	3
0.5	1	-	-	-	-	-	-	-	-	.13E3	.76E6	.33E7
	2	-	-	-	-	-	-	-	-	.15E3	.75E6	.33E7
	3	-	-	-	-	-	-	-	-	15E3	.79E6	.33E7
1	1	-	-	14	17.8	-	-	2	2.9	.6E3	.167E7	.167E7
	2	-	-	13 7	16.8	-	-	2	2 7	.66E3	.167E7	.167E7
	3	-	-	14	17.9	-	-	2	3	66E3	.167E7	167E7
2	1	-	8.6	11.6	14.6	-	1.4	2.1	2 9	.58E5	.83E6	83E6
	2	-	8 5	11	12 7	-	1.4	2	2 5	.65E5	.83E6	.85E6
	3	-	8.7	11.7	14 8	-	1.4	2.2	3	.65E5	85E6	.85E6
3	1	-	7.5	10 1	13 2	-	1 4	2	2 7	.2E6	.56E6	.56E6
	2	-	7.4	9.2	10 6	-	1.4	1 8	2 1	.23E6	56E6	.56E6
	3	-	7 7	10 4	13.6	-	1 4	2.1	2 8	.23E6	.56E6	.56E6
4	1	3.5	6 7	9.2	12.6	53	1.3	1.9	2.4	32E6	.42E6	.42E6
	2	3 6	6 6	8.2	9.3	56	1.3	1 7	1.9	.37E6	.42E6	.42E6
	3	3 6	6 9	9 6	13.3	56	1.34	2	2.5	37E6	.42E6	42E6
5	1	3 15	6	8 5	12.2	51	1.2	1.7	2.2	.33E6	33E6	33E6
	2	3.3	6	7.3	8.2	.55	1.2	1 5	1.7	33E6	.33E6	33E6
	3	3.3	6.4	8.9	12.8	55	1.3'	1.8	2.3	.33E6	.33E6	.33E6

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- Δ Θ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold

Table 5-9
S-Band Broadcast Communication Capacity
TIME ZONE

Xmit Antenna dia = 9.1m

Δθ	Gain Model Case	VOICE Rec:Dia 0.6	1.8	3	4.6	TV 0.6	1.8	3	4.6	DATA 0.6	7.8	3
0.5	1	-	-	-	-	-	-	-	-	-	.77E3	.23E5
	2	-	-	-	-	-	-	-	-	-	.76E3	.22E5
	3	-	-	-	-	-	-	-	-	-	.78E3	.23E5
1	1	-	-	-	-	-	-	-	-	-	.3E5	.167E7
	2	-	-	-	-	-	-	-	-	-	"	"
	3	-	-	-	-	-	-	-	-	-	"	"
2	1	-	-	6.6	8.4	-	-	95	1.35	.22E3	.83E6	.83E6
	2	-	-	6.4	8	-	-	.92	1.3	.23E3	"	"
	3	-	-	6.6	8.4	-	-	.95	1.4	"	"	"
3	1	-	4.4	5.9	7.5	-	.6	.95	1.35	.72E4	.56E6	.56E6
	2	-	4.3	5 7	7	-	.6	.94	1.2	.76E4	"	"
	3	-	4.4	5.9	7.6	-	.6	.98	1.4	"	"	"
4	1	-	4	5 5	6 9	-	.65	.98	1.35	.36E5	.42E6	.42E6
	2	-	4	5.2	6.3	-	.64	.93	1.2	.38E5	"	"
	3	-	4	5.5	6.9	-	65	1	1.4	"	"	"
5	1	-	3 8	5	6.5	-	65	98	1.35	.88E5	.33E6	33E6
	2	-	3.8	4.8	5.6	-	64	9	1.1	93E5	"	"
	3	-	3.8	5	6.6	-	.65	1	1.4	"	"	"

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/Intersatellite spacing, deg)
- Δ θ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold (or data capacity very small)

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Table 5-10

S-Band Broadcast Communication Capacity

Xmt Antenna Dia=9 1m

TIME ZONE-Sharp Satellite Beam

Δθ	Gain Model Case	VOICE Rec Dia 0.6	1.8	3	4.6	TV 0.6	1.8	3	4.6	DATA 0.6	1.8	3
0.5	4	-	43.5	58.5	76	-	7.9	11.6	15.3	2E7	.33E7	.33E7
	5	-	43.5	58.5	76	-	7.9	11.6	15.3	"	"	"
	6	-	43.5	58.5	76	-	7.9	11.6	15.3	"	"	"
1	4	13.8	26.3	36.5	50	2	5.2	7.4	9.6	.167E7	.167E7	.167E7
	5	13.8	26.3	36.5	50	2	5.2	7.4	9.6	"	"	"
	6	13.8	26.3	36.5	50	2	5.2	7.4	9.6	"	"	"
	4	8.3	16.1	23	35	1.4	3.3	4.6	5.7	83E6	83E6	.83E6
	5	8.3	16.1	23	35	1.4	3.3	4.6	5.7	"	"	"
	6	8.3	16.1	23	35	1.4	3.3	4.6	5.7	"	"	"
3	4	6.2	12.1	18	25	1	2.5	3.4	4.2	.56E6	56E6	56E6
	5	6.2	12.1	18	25	1	2.5	3.4	4.2	"	"	"
	6	6.2	12.1	18	35	1	2.5	3.4	4.2	"	"	"
4	4	5.1	10	15	19	1	2	2.8	3.3	42E6	42E6	42E6
	5	5.1	10	15	19	1	2	2.8	3.3	"	"	"
	6	5.1	10	15	19	1	2	2.8	3.3	"	"	"
5	4	4.3	8.4	12.5	15	8	1.8	2.3	2.8	.33E6	33E6	33E6
	5	4.3	8.4	12.5	15	8	1.8	2.3	2.8	"	"	"
	6	4.3	8.4	12.5	15	.8	1.8	2.3	2.8	"	"	"

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/Intersatellite spacing, deg)
- $\Delta\theta$ - is the intersatellite spacing in degrees
- Antenna diameters are in meters
- (-) - Dash indicates System below threshold

Table 5-11

K-Band Fixed Service Communication Capacity

CONUS

ΔΘ	Gain Model Case	VOICE Dia 3	4.6	7	9.14	TV 3	4.6	7	9.14	DATA 3	4.6	7
5	1	-	-	-	-	-	-	-	-	.4E6 (.85E5)	.1E7 (.2E6)	.24E7 (.48E6)
	2	-	-	-	-	-	-	-	-	.38E6 (.75E5)	.9E6 (.18E6)	.2E7 (.4E6)
	3	-	-	-	-	-	-	-	-	.4E6 (.85E5)	.1E7 (.2E6)	.24E7 (.48E6)
1	1	25 (15)	32 (20)	41 (25)	48 (30)	14 (-)	18.6 (10)	24 (14)	2.8 (17)	.167E7 (.1E7)	.167E7 (")	.167E7 (.167E7)
	2	21 (-)	23 (14)	24.6 (15)	25 (15.5)	10 (-)	12 (-)	12.4 (6.2)	12.7 (6.4)	.167E7 (.9E6)	.167E7 (")	.167E7 (")
	3	25 (15)	32 (20)	41 (25)	48 (30)	14 (-)	18.6 (10)	24 (14)	28 (17)	.167E7 (.1E7)	.167E7 (")	.167E7 (")
2	1	14 (9)	18 (12)	23 (15)	26 (17)	9 (5)	12 (7)	15 (9.3)	17 (11)	.83E6 (.6E6)	.83E6 (")	.83E6 (")
	2	12.4 (7.7)	14 (9)	15 (9.3)	15.4 (9.5)	7 (-)	7.7 (4)	8.1 (4.3)	8.3 (4.4)	.83E6 (.57E6)	.83E6 (")	.83E6 (")
	3	14 (9)	18 (12)	23 (15)	26 (17)	9 (5)	12 (7)	15 (9.3)	17 (11)	.83E6 (.6E6)	.83E6 (")	.83E6 (")
3	1	10 (6)	12.5 (8)	15.5 (10)	17.5 (12)	6.5 (3.5)	8 (5)	10.5 (6.6)	12 (8)	.56E6 (.4E6)	.56E6 (")	.56E6 (")
	2	8.9 (5.5)	10 (6)	11 (6.8)	11.5 (7)	5 (2.6)	5.7 (3)	6.1 (3.3)	6.3 (3.4)	.56E6 (.4E6)	.56E6 (")	.56E6 (")
	3	10 (6)	12.5 (8)	15.5 (10)	17.5 (12)	6.5 (3.5)	8 (5)	10.5 (6.6)	12 (8)	.56E6 (.4E6)	.56E6 (")	.56E6 (")
4	1	7.5 (5)	9.5 (6)	12 (7.6)	13 (9)	5 (2.7)	6.4 (4)	8 (5)	9 (6)	.42E6 (.3E6)	.42E6 (")	.42E6 (")
	2	6.7 (4.2)	8 (5)	8.9 (5.5)	9.3 (5.7)	4 (2.1)	4.7 (2.5)	5 (2.8)	5.2 (2.9)	.42E6 (.3E6)	.42E6 (")	.42E6 (")
	3	7.5 (5)	9.5 (6)	12 (7.6)	13 (9)	5 (2.7)	6.4 (4)	8 (5)	9 (6)	.42E6 (.3E6)	.42E6 (")	.42E6 (")
5	1	6 (4)	7.6 (5)	9 (6)	10.5 (7)	4 (2.2)	5.2 (3)	6.4 (4)	7 (4.8)	.33E6 (.24E6)	.33E6 (")	.33E6 (")
	2	5.5 (3.5)	6.5 (4)	7.3 (4.6)	7.8 (4.8)	3.3 (1.8)	4 (2.1)	4.2 (2.3)	4.3 (2.4)	.33E6 (.24E6)	.33E6 (")	.33E6 (")
	3	6 (4)	7.6 (5)	9 (6)	10.5 (7)	4 (2.2)	5.2 (3)	6.4 (4)	7 (4.8)	.33E6 (.24E6)	.33E6 (")	.33E6 (")

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- $\Delta\theta$ - is the intersatellite spacing in degrees
- Antenna diameters are in meters (Receive and transmit antenna diameters are equal)
- (-) - Dash indicates System below threshold
- (•) The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7dB while the interfering downlinks have not faded.

Table 5-12

K-Band Fixed Service Communication Capacity

TIME ZONE

ΔΘ	Gain Model Case	VOICE Dia 3	4.6	7	9.14	TV 3	4.6	7	9.14	DATA 3	4.6	7
0.5	1	-	-	-	-	-	-	-	-	.1E6 (.2E5)	.27E6 (.5E5)	.64E6 (.13E6)
	2	-	-	-	-	-	-	-	-	.98E5 (.2E5)	.24E6 (.5E5)	.57E6 (.1E6)
	3	-	-	-	-	-	-	-	-	.1E6 (.2E5)	.27E6 (.5E5)	.64E6 (.13E6)
1	1	21 (13)	27 (17)	36 (22)	43 (25)	10 (-)	14.2 (7.3)	19 (10.5)	23 (13)	.167E7 (")	.167E7 (")	.167E7 (")
	2	18 (-)	20 (-)	22 (13.4)	22.4 (13.7)	8 (-)	9.5 (-)	10.4 (5.1)	10.7 (5.3)	167E7 (")	.167E7 (")	.167E7 (")
	3	21 (13)	27 (17)	36 (22)	43 (25)	10 (-)	14.2 (7.3)	19 (10.5)	23 (13)	.167E7 (")	.167E7 (")	.167E7 (")
2	1	16 (10)	21 (13)	29 (17)	34 (20)	9 (5)	12 (7)	15 (9.5)	17 (")	.83E6 (")	.83E6 (")	83E6 (")
	2	12.5 (7.7)	13 (8.2)	14 (8.5)	14 (8.6)	6.3 (3.2)	6.9 (3.5)	7.1 (3.7)	7.2 (3.7)	.83E6 (")	.83E6 (")	.83E6 (")
	3	16 (10)	21 (13)	29 (17)	34 (20)	9 (5)	12 (7)	15 (9.5)	17 (")	.167E7 (")	.167E7 (")	.167E7 (")
3	1	13 (8)	16.5 (10.3)	21 (13)	23 (15)	8 (4.4)	9.8 (6)	12 (8)	13 (9)	.56E6 (")	.56E6 (")	.56E6 (")
	2	9.5 (6)	10 (6.3)	10.5 (6.5)	10.6 (6.5)	5.1 (2.7)	5.4 (2.9)	5.6 (3)	5.6 (3)	.56E6 (")	.56E6 (")	.56E6 (")
	3	13 (8)	16.5 (10.3)	21 (13)	23 (15)	8 (4.4)	9.8 (6)	12 (8)	13 (9)	.56E6 (")	.56E6 (")	.56E6 (")
4	1	10 (6.6)	13 (8.3)	16 (10.6)	17 (12)	6.5 (3.8)	8 (5)	9.6 (6.7)	10 (7.6)	.42E6 (")	.42E6 (")	.42E6 (")
	2	7.8 (5)	8.4 (5.2)	8.7 (5.3)	8.8 (5.3)	4.3 (2.3)	4.6 (2.5)	4.7 (2.5)	4.7 (2.5)	.42E6 (")	.42E6 (")	.42E6 (")
	3	10 (6.6)	13 (8.3)	16 (10.6)	17 (12)	6.5 (3.8)	8 (5)	9.6 (6.7)	10 (7.6)	.42E6 (")	.42E6 (")	.42E6 (")
5	1	8.5 (5.4)	10.5 (7)	13 (8.7)	14 (10)	5.5 (3.3)	7 (4.4)	8 (5.6)	8.6 (6.4)	.33E6 (")	33E6 (")	.33E6 (")
	2	6.6 (4)	7 (4.4)	7.4 (4.5)	7.5 (4.5)	3.7 (2)	3.9 (2.1)	4 (2.2)	4 (2.2)	.33E6 (")	.33E6 (")	.33E6 (")
	3	8.5 (5.4)	10.5 (7)	13 (8.7)	14 (10)	5.5 (3.3)	7 (4.4)	8 (5.6)	8.6 (6.4)	.33E6 (")	.33E6 (")	33E6 (")

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/Intersatellite spacing, deg)
- $\Delta \Theta$ - is the intersatellite spacing in degrees
- Antenna diameters are in meters (Receive and Transmit antenna diameters are equal)
- (-) - Dash indicates System below threshold
- (•) The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7dB while the interfering downlinks have not faded.

Table 5-13

K-Band Fixed Service Communication-Capacity

TIME ZONE - SHARP SATELLITE BEAM

Δ Θ	Gain Model Case	VOICE				TV				DATA		
		Dia. 3	4.6	7	9.14	3	4.6	7	9.14	3	4.6	7
0.5	4	86 (54)	105 (70)	126 (87)	139 (100)	55 (33)	68 (45)	80 (57)	87 (65)	.33E7 (")	.33E7 (")	.33E7 (")
	5	"	"	"	"	"	"	"	"	"	"	"
	6	"	"	"	"	"	"	"	"	"	"	"
1	4	43 (28)	53 (36)	63 (45)	70 (50)	29 (18)	35 (23)	41 (30)	44 (34)	.167E7 "	.167E7 "	.167E7 "
	5	"	"	"	"	"	"	"	"	"	"	"
	6	"	"	"	"	"	"	"	"	"	"	"
2	4	22 (14)	27 (18)	32 (22)	35 (25)	15 (9)	18 (12)	21 (15)	22 (17)	.83E6 "	.83E6 "	.83E6 "
	5	"	"	"	"	"	"	"	"	"	"	"
	6	"	"	"	"	"	"	"	"	"	"	"
3	4	15 (9.5)	18 (12)	21 (15)	23 (17)	10 (6)	12 (8)	14 (10)	15 (11.5)	.56E6 (")	.56E6 (")	.56E6 (")
	5	"	"	"	"	"	"	"	"	"	"	"
	6	"	"	"	"	"	"	"	"	"	"	"
4	4	11 (7.1)	13.4 (9)	16 (11.3)	17.4 (12.7)	7.5 (4.7)	9 (6)	10.5 (7.7)	11.3 (8.7)	.42E6 (")	.42E6 (")	.42E6 (")
	5	"	"	"	"	"	"	"	"	"	"	"
	6	"	"	"	"	"	"	"	"	"	"	"
5	4	9 (5.7)	11 (7.3)	13 (9)	14 (10)	6 (3.8)	7.3 (5)	8.4 (6.2)	9 (7)	.33E6 (")	.33E6 (")	.33E6 (")
	5	"	"	"	"	"	"	"	"	"	"	"
	6	"	"	"	"	"	"	"	"	"	"	"

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- Δ Θ - is the intersatellite spacing in degrees
- Antenna diameters are in meters (Receive and Transmit antenna diameters are equal)

- (•) The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7dB while the interfering downlinks have not faded.

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Table 5-14

S-Band Fixed Service Communication Capacity

CONUS

ΔΘ	Gain Model Case	VOICE Dia. 3	4.6	7	9.14	TV 3	4.6	7	9.14	DATA 3	4.6	7
0.5	1	-	-	-	-	-	-	-	-	.4E6	.172E7	.33E7
	2	-	-	-	-	-	-	-	-	.39E6	.157E7	.33E7
	3	-	-	-	-	-	-	-	-	.42E6	.174E7	.33E7
1	1	-	16.2	20.9	24.5	-	2.6	3.7	4.6	.167E7	.167E7	167E7
	2	-	15.5	18.9	21	-	2.4	3.2	3.7	.167E7	167E7	.167E7
	3	-	16.2	20.9	24.6	-	2.6	3.7	4.6	.167E7	.167E7	.167E7
2	1	10.1	12.8	16.7	20	1.8	2.6	3.5	4.1	.83E6	.83E6	.83E6
	2	9.7	11.9	13.7	14.7	1.7	2.3	2.8	2.9	.83E6	.83E6	83E6
	3	10.2	12.9	16.9	20.2	1.8	2.6	3.5	4.2	83E6	.83E6	.83E6
3	1	8.4	10.8	14.1	16.9	1.7	2.3	3	3.5	56E6	.56E6	.56E6
	2	8	9.5	10.9	11.6	1.6	2	2.3	2.4	.56E6	56E6	.56E6
	3	8.5	11	14.3	17.1	1.7	2.4	3	3.6	.56E6	.56E6	.56E6
4	1	7	9.2	11.8	13.8	1.5	2	2.6	3	.42E6	.42E6	.42E6
	2	6.7	8	9.1	9.7	1.4	1.7	1.9	2	.42E6	.42E6	.42E6
	3	7.2	9.3	11.9	13.9	1.6	2	2.7	3	.42E6	.42E6	.42E6
5	1	6	7.8	9.9	11.4	1.4	1.8	2.3	2.6	.33E6	.33E6	.33E6
	2	5.7	6.8	7.8	8.2	1.4	1.5	1.6	1.7	.33E6	.33E6	.33E6
	3	6.2	7.9	10	11.4	1.4	1.8	2.3	2.6	33E6	.33E6	.33E6

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/Intersatellite spacing, deg)
- $\Delta\Theta$ - is the intersatellite spacing in degrees
- antenna diameters are in meters (Receive and Transmit antenna diameters are equal)
- (-) - Dash indicates System below threshold
- (•) The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7dB while the interfering downlinks have not faded.

Table 5-15

S-Band-Fixed-Service-Communication-Capacity

TIME ZONE

Δθ	Gain Model Case	VOICE Dia. 3	4.6	7	9.14	TV 3	4.6	7	9.14	DATA 3	4.6	7
0.5	1	-	-	-	-	-	-	-	-	.12E4	.98E4	.4E5
	2	-	-	-	-	-	-	-	-	.12E4	.9E4	.39E5
	3	-	-	-	-	-	-	-	-	.12E4	.98E4	.4E5
1	1	-	-	-	13.9	-	-	-	2.1	.78E5	.15E7	.167E7
	2	-	-	-	13.1	-	-	-	1.9	.75E5	.14E7	.167E7
	3	-	-	-	13.9	-	-	-	2.1	.8E5	.15E7	"
2	1	-	7.7	10	11.7	-	1.2	1.7	2.2	.83E6	.83E6	.83E6
	2	-	7.5	9.2	10.2	-	1.1	1.5	1.8	"	"	"
	3	-	7.7	10	11.7	-	1.2	1.7	2.2	"	"	"
3	1	5.3	7	8.8	10.4	.8	1.2	1.7	2.1	.56E6	.56E6	.56E6
	2	5.2	6.5	7.8	8.3	.8	1.1	1.4	1.6	"	"	"
	3	5.4	7	8.8	10.5	.8	1.2	1.7	2.1	"	"	"
4	1	4.9	6.2	8.2	9.8	.8	1.2	1.7	2	.42E6	.42E6	.42E6
	2	4.8	5.9	6.8	7.3	.8	1.1	1.3	1.5	"	"	"
	3	4.9	6.2	8.2	9.8	.8	1.2	1.7	2	"	"	"
5	1	4.5	5.8	7.7	9.3	.8	1.2	1.6	1.9	.33E6	.33E6	.33E6
	2	4.4	5.2	6.1	6.4	.8	1.1	1.2	1.3	"	"	"
	3	4.6	5.9	7.7	9.4	.8	1.2	1.6	1.9	"	"	"

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/ Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- Δ θ - is the intersatellite spacing in degrees
- Antenna diameters are in meters (Receive and Transmit antenna diameters are equal)
- (-) - Dash indicates System below threshold
- ( ) The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7dB while the interfering downlinks have not faded.

Table 5-16

S-Band Fixed Service Communication Capacity

TIME ZONE - SHARP SATELLITE BEAM

Δθ	Gain Model Case	VOICE Dia. 3	VOICE 4.6	VOICE 7	VOICE 9.14	TV 3	TV 4.6	TV 7	TV 9.14	DATA 3	DATA 4.6	DATA 7
0.5	4	-	-	88	111	-	-	18	21	.3E6	.7E6	.3E7
	5	-	-	"	"	-	-	"	"	"	"	"
	6	-	-	"	"	-	-	"	"	"	"	"
1	4	30	39	52	63	6.3	8 5	11	12	.167E7	.167E7	.167E7
	5	30	"	"	"	6.3	"	"	"	"	"	"
	6	30	"	"	"	6.3	"	"	"	"	"	"
2	4	17	22	28	33	3.8	5	6	7	.83E6	.83E6	.83E6
	5	17	"	"	"	3.8	"	"	"	"	"	"
	6	17	"	"	"	3.8	"	"	"	"	"	"
3	4	12	15.5	19	22	2.8	3.6	4.3	5	.56E6	.56E6	.56E6
	5	12	"	"	"	2.8	"	"	"	"	"	"
	6	12	"	"	"	2.8	"	"	"	"	"	"
4	4	9.4	12	15	17	2.2	2.8	3.4	3.8	.42E6	.42E6	.42E6
	5	9.4	"	"	"	2.2	"	"	"	"	"	"
	6	9.4	"	"	"	2.2	"	"	"	"	"	"
5	4	7.7	9.7	12	13	1.8	2.3	2.8	3	.33E6	.33E6	.33E6
	5	7.7	"	"	"	1.8	"	"	"	"	"	"
	6	7.7	"	"	"	1.8	"	"	"	"	"	"

- Voice - The numbers represent (voice channels per MHZ/ Intersatellite spacing, deg)
- TV - The numbers represent (TV channels in 500 MHZ BW/Intersatellite spacing, deg)
- Data - The numbers represent (Bit Rate per MHZ/ Intersatellite spacing, deg)
- Δθ - is the intersatellite spacing in degrees
- Antenna diameters are in meters (Receive and transmit antenna diameters are equal)
- (-) - Dash indicates System below threshold
- (•) The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7dB while the interfering downlinks have not faded.

Table 5-17

Multicarrier Fixed Service Communications Capacity

#Carriers = 6 (6MHz BW)
Rec: Antenna dia. = 9.1 m
Xmt Antenna dia. = 9.1 m

CONUS

Δ θ	Gain Model Case	K-BAND Voice	K-BAND Data	S-BAND Voice	S-BAND Data	UHF BAND Voice	UHF BAND Data
0.5	1	-	-	-	-	-	
	2						
	3						
1	1	16 (-)	.167E7 (.86E6)	-	.12E6	-	
	2	10 (-)	.1E7 (.38E6)	-	.9E5	-	
	3	16 (-)	.167E7 (.86E6)	-	.12E6	-	
2	1	9.9 (6.2)	.83E6 (.52E6)	5.3	.57E6	-	.12E4
	2	6.7 (-)	.83E6 (.33E6)	4.6	.42E6	-	.11E4
	3	9.8 (6.2)	.83E6 (.52E6)	5.3	.57E6	-	.12E4
3	1	6.8 (4.5)	.56E6 (.35E6)	4.8	.56E6	-	.9E4
	2	5 (-)	.56E6 .26E6	4.1	.52E6	-	.85E4
	3	6.8 (4.5)	.56E6 (.35E6)	4.8	.56E6	-	.94E4
4	1	5.2 (3.4)	.42E6 (.26E6)	4.2	.42E6	-	.16E5
	2	4 (-)	.42E6 (.22E6)	3.6	.42E6	-	.15E5
	3	5.2 (3.4)	.42E6 (.26E6)	4.2	.42E6	-	.16E5
5	1	4.2 (2.8)	.33E6 (.21E6)	3.6	.33E6	-	.33E5
	2	3.4 (2)	.33E6 (.18E6)	3.1	.33E6	-	.31E5
	3	4.2 (2.8)	.33E6 (.21E6)	3 6	.33E6	-	.35E5

- o Voice - The numbers represent (voice channels per MHz/Intersatellite spacing, deg)
- o Data - The numbers represent (Bit Rate per MHz/Intersatellite spacing, deg)
- o Δ θ - is the Intersatellite spacing in degrees.
- o (-) - Dash indicates system below threshold (or data capacity very small)
- o (•) - The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7 dB while the interfering downlinks have not faded.

Table 5-18

Multicarrier Fixed Service Communications Capacity

#Carriers = 6 (6MHz BW)
Rec: Antenna dia. = 9.1 m
Xmt Antenna dia. = 9 1 m

Time Zone

Δ θ	Gain Model Case	K-BAND		S-BAND		UHF BAND	
		Voice	Data	Voice	Data	Voice	Data
0 5	1	-	.2E5 (.14E5)	-	.2E4	-	-
	2	-	.18E5 (.13E5)	-	.18E4	-	-
	3	-	2E5 (.14E5)	-	.2E4	-	-
1	1	23 (17)	.167E7 (")	9	1E7	-	.2E3
	2	16 (8.7)	.167E7 (')	8.3	.9E6	-	.2E3
	3	23 (17)	.167E7 (")	9	.1E7	-	2E3
2	1	12 (10)	.83E6 (")	8.2	.83E6	-	.35E5
	2	9.5 (5.9)	83E6 (")	7.2	.83E6	-	.34E5
	3	12 (10)	.83E6 (")	8.2	.83E6	-	.35E5
3	1	8 (7)	.56E6 (")	6 8	.56E6	-	.15E6
	2	6.9 (4.5)	56E6 (")	5.9	56E6	-	.14E6
	3	8 (7)	.56E6 (")	6.8	.56E6	-	.15E6
4	1	6.2 (5.4)	.42E6 (")	5.5	.42E6	2 3	26E6
	2	5.4 (3.7)	.42E6 (")	4.9	.42E6	2 3	.26E6
	3	6.2 (5.4)	42E6 (")	5.5	.42E6	2.3	27E6
5	1	5 (4.3)	33E6 (")	4.6	.33E6	2.3	.33E6
	2	4.4 (3)	.33E6 (")	4.1	33E6	2.3	33E6
	3	5 (4 3)	.33E6 (")	4.6	33E6	2.3	.33E6

o Voice - The numbers represent (voice channels per MHz/Intersatellite spacing, deg)
o Data - The numbers represent (Bit Rate per MHz/Intersatellite spacing, deg)
o Δ θ - is the Intersatellite spacing in degrees.
o (-) - Dash indicates system below threshold (or data capacity very small)
o (•) - The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7 dB while the interfering downlinks have not faded.

Table 5-19

Multicarrier Fixed Service Communications Capacity

#Carriers = 6 (6MHz BW)
Rec: Antenna dia. = 9.1 m
Xmt Antenna dia. = 9.1 m

Time Zone - Sharp Satellite Beam

Δ θ	Gain Model Case	K-BAND Voice	K-BAND Data	S-BAND Voice	S-BAND Data	UHF BAND Voice	UHF BAND Data
0.5	4	50 (43)	.33E7 (")	47	.33E7	-	.18E5
	5	"	"	"	"	-	"
	6	"	"	"	"	-	"
1	4	25 (22)	.167E7 (")	24	.167E7	17.2	.167E7
	5	"	"	"	"	"	"
	6	"	"	"	"	"	"
2	4	12 (")	.83E6 (")	12	.83E6	9.8	.83E6
	5	"	"	"	"	"	"
	6	"	"	"	"	"	"
3	4	8 (7)	.56E6 (")	8.1	.56E6	6.9	.56E6
	5	"	"	"	"	"	"
	6	"	"	"	"	"	"
4	4	6 (5.5)	.42E6 (")	6.1	.42E6	5.3	.42E6
	5	"	"	"	"	"	"
	6	"	"	"	"	"	"
5	4	5 (4.3)	.33E6 (")	4.9	.33E6	4.3	.33E6
	5	"	"	"	"	"	"
	6	"	"	"	"	"	"

o Voice - The numbers represent (voice channels per MHz/Intersatellite spacing, deg)
o Data - The numbers represent (Bit Rate per MHz/Intersatellite spacing, deg)
o Δ θ - is the Intersatellite spacing in degrees.
o (-) - Dash indicates system below threshold
o (•) - The numbers within the parenthesis indicate the capacity when the desired downlink has faded by 7 dB while the interfering downlinks have not faded.

SECTION 6

TECHNOLOGY IMPACT (to 1985)

6.1 INTRODUCTION:

This section summarizes earth station, satellite and system technology which is believed to be significant for the cost-effective realization of the services described in this study. While this technology applies principally to the so-called small user, which restricts earth station technology essentially to that of small, low cost earth stations, it may also impact larger users through more efficient satellite or system design. It will be recalled that economy of scale is an important factor in service cost. For earth stations this is reflected in unit cost reductions for quantity "buys". For satellites, this is reflected in the economy of larger satellites on the basis that larger multi-purpose, multi-frequency band, or multi-service satellites cost less in terms of annual cost per user than do smaller satellites (provided the larger satellites are reasonably utilized). This economy of scale has been discussed elsewhere in this study and will not be discussed further in this section. This section will be confined to discussions on technology.

A prediction of technology performance out to 1985 is subject to some conjecture even if there is a reasonable consensus on the nature of future development and funding. Some development may be needed to achieve the performance and/or costs used in this study and presumably these developments will be funded and will be successful. The state-of-the-art may even progress faster than anticipated. These uncertainties should be accepted by the reader. This section does not discuss minor device improvements that may be expected to routinely occur or certain non-recurring costs necessary to achieve the stated service performance and costs but rather areas where concentrated R&D might achieve significant improvements. Emphasis, therefore, is placed only on technology which can make a significant difference in terms of cost-effectiveness, or performance. On the other hand, it also is important to recognize technological areas which have matured to the point where additional R&D investment will reap relatively small dividends. Therefore, this summary section is intended to highlight fruitful areas for R&D expenditures either by the public or private sectors. There are three pertinent areas, earth stations including interface equipment, satellites and launch vehicles, and systems. Each of these three areas will be discussed in the following sections. Much of the following summary is elaborated upon in more detail in Volume 3.

6.2 EARTH STATION TECHNOLOGY

Earth Station Technology is divided into four major subsystems, the antenna, LNR, HPA and interface. In general, the antenna, LNR and HPA technology

are mature technologies and present experience and the supplier surveys did not disclose any prospects of a revolutionary nature, although there are small improvements being accomplished by suppliers in each of the subsystem areas, and there are novel components and subsystems which improve cost-effectiveness and/or performance. With regard to interface equipment, there are significant cost reductions in progress for digital subsystems and components due to an evolving LSI industry. If sufficient production is available to pay for the non-recurring costs, production costs of digital circuitry can be reduced substantially. Unfortunately improvements due to LSI in analogue circuits are not comparable to those in digital circuits so that in general overall cost reductions depend on how much of the total system is digital, and how much of the "digital" system is really composed of digital logic.

A. Earth Station Antennas.

While new methods for fabricating and erecting low-cost antennas are constantly being sought, and certain technical developments relating to antenna efficiency and side lobe control are currently active, the conclusions reached with respect to antenna technology is that this is a mature technology and only minor improvements in low-cost earth station antennas are to be expected out to 1985. The most significant improvement in antenna technology relates to control of antenna side-lobes. While this does not seriously affect the performance and cost-effectiveness of the services in this study, it does have serious consequences regarding the ultimate orbit capacity achievable and this is of concern to all users. Manifestations of this problem are currently experienced in the U.S. at C-Band, where the FCC has limited the deployment of small apertures and placed at least implicit limits on minimun antenna diameters (approximately 4.5 meters). These restrictions have hindered development (or commitment) to systems utilizing small apertures - such as radio networks and point-to point data applications using small terminals. In addition, the 1977 WARC has indicated similar concern regarding Ku-Band, resulting, in Region II, in the orbital separation of fixed service and broadcast service satellites, and in Region I, with recommendations on minimum acceptable G/T ratios, as well as coordination guide-lines for both regions. Consequently, R&D relating to the use of antenna shrouds, absorbers, complicated illumination factors, arrayed feeds, etc. in the context of small antennas to supress sidelobes (or at least close in sidelobes) can ultimately be important. However, the possible performance improvements achievable by concerted R&D are probably dwarfed by the magnitude of the cost uncertainties of large-scale production.

With regard to the land mobile service, however, R&D is recommended to develop and test suitable antennas. Not only must these antennas achieve significant performance in gain and beamwidth and be cost-effective as well, but they also must satisfy other important requirements. Among these are: (1) immunity to windage and weather, (2) immunity to vandalism, (3) the ability to be esthetically pleasing (depending on the type of vehicle on which it is mounted), (4) no restrictions on vehicle access or right-of-way, (5) low-cost installation. Other technical issues of equal importance are performance in field service with regard to ground and obstacle multipath, obstruction loss characteristic of various types (such as trees, wood buildings, open steelwork bridges) which may intercept the satellite-vehicle path. These problems which are only treated perfunctorily herein are deserving of a concerted R&D effort.

B. Low Noise Receivers:

Most of the service tradeoffs identify FET low noise receivers as an optimum choice. Such receivers bridge the gap between high performance and high cost paramp and low performance, low cost mixers, thereby superseding tunnel diodes. FET low noise performance is constantly improving. At C-Band, where FET development is now exceedingly active, FET performance is approaching paramp performance. Unit amplifier noise temperature is below 100^{o}K. While not as active presently, similar progress is expected in Ku-Band. The FET amplifier is inherently a low-cost unit. It is a two-port device with reasonable impedances, requiring simple low-cost stub tuning readily provided by high performance, low-cost, reproducible microstrip circuitry. Paramps, in addition to requirements for a high frequency pump (60 GHz or better) are single port devices requiring complex RF junctions and complex RF circuitry. Consequently, design, production and test costs are significantly higher. In addition, experience indicates that FETs can be field replaceable on a modular basis (that is, amplifier by amplifier) whereas troubleshooting and repairing paramps is much more difficult. Nevertheless, despite these attractive possibilities, the advent of FETs has not resulted in a dramatic reduction in the cost of "G/T". Comparisons of G/T vs cost with previous studies(1) indicates that inclusion of current FET capability does not substantially change the G/T vs. cost curve. Consequently, it is concluded that while FETs are a definite advantage and have wide application, this device will not have a substantial effect on the economic viability of the various services. Some attention has been given to image enhanced mixers which are capable of moderate noise performance. However the computer tradeoffs seldom result in the selection of this device because of its relatively high cost. Like the paramp, the image terminated mixer requires a complicated microwave circuit which is expensive to design, manufacture and test. All in all, FET development is proceeding at a rapid pace and while Ku-Band FET development might be enhanced by additional R&D the study results show this is unlikely to have a serious impact on the service cost-effectiveness.

C. Earth Station High Power Amplifiers.

Wideband interactive user services require a significant amount of transmitter power, greater than 10 watts, which appears only possible with tube technology (TWTs or Klystrons). Tube technology is mature, the supplier industry is producing tubes in substantial quantities, and this industry is highly competitive, so that significant technological improvement affecting cost or performance out to 1985 are not expected.

A dominant part of tube-type HPA cost is the high voltage power supplies and control circuitry. The former are large, high voltage units, some of which must provide precise regulation. Above 30 watts, sequencing units, overload tripouts and "crowbars" significantly add to the expense. Both the high voltage circuits and the control circuitry even though built to commercial practices require frequent maintenance. Typical tube lifetimes are 10,000 hours (and often are less), and skilled personnel are required to perform maintenance because of the mechanical assembly complexities and the complexity of electrical adjustments.

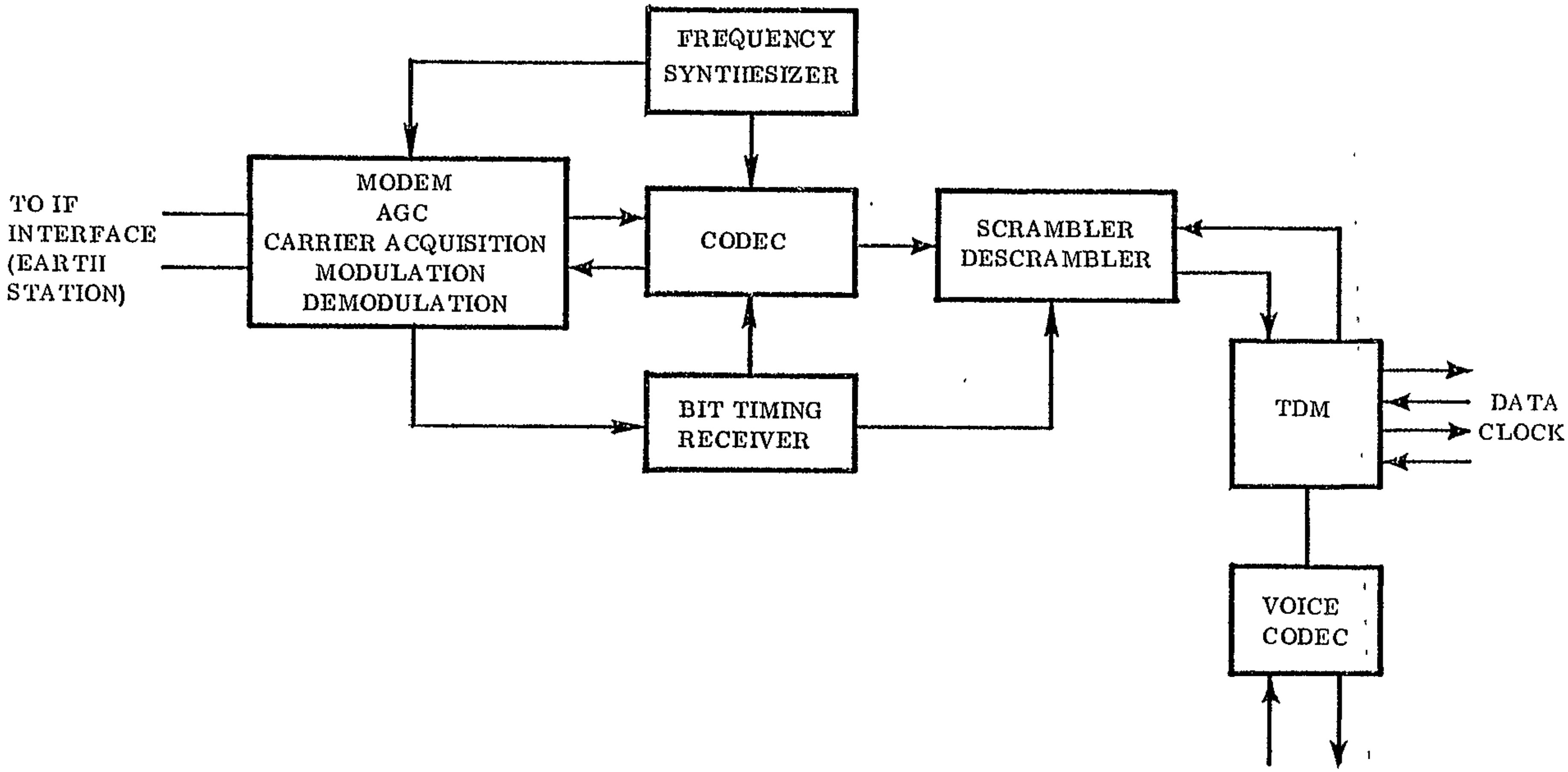

Figure 6-1. Block Diagram of SCPC Digital Channel Unit.

On the other hand, narrow band interactive services can use solid state amplifiers at levels of less than 10 watts. Both IMPATT and FET devices are attractive and both reduce costs compared to tubes and simplify servicing because there are no high voltage power supplies. Solid state HPAs consist of several stages in cascade, e.g., modular so that module replacement is simplified and unlike tubes, there are essentially no wearout mechanisms. IMPATT amplifiers, of course, are not new; however, recently improved devices, both in Silicon and Gallium Arsenide are available. The FET amplifier will likely be favored in future applications because circuitry is simpler to build and test and FET two-port devices are simpler to design, particularly over narrow bands.

No significant changes in HPA technology is expected through 1985. The availability of solid state HPAs, while helpful in narrow band interactive systems, does not have a major influence on system costs because HPA costs in this case are small in relation to the total earth station.

D. Interface Equipment.

This is a complex assortment of multi-functional equipment that can be a dominant cost in the earth stations of some services. For example, the compressed TV teleconferencing application involves vidicons, cameras, special lighting, possibly "video compressors", accompanying TV monitors, MODEMS, TV/audio diplexers, etc., as well as the normal earth station components. All this equipment is readily available commercially and is manufactured on a scale that is likely to be unaffected by demands for satellite/video teleconferencing equipment. The same is true for the other teleconferencing systems and for the multiple data and voice service. Consequently, technological break throughs significantly affecting cost and performance characteristics are not really expected except for one very important item, and that is LSI.

The development and use of LSI has caused a truly remarkable revolution in the microprocessor (communications) field and in the pocket calculator. In fact, wherever low cost, high production of digital logic circuits is required, LSI is the preferred answer. Unfortunately, while the two examples given above are dramatic, the "wholesale" application of LSI to earth station interface equipment, even so called digital interface equipment is not possible. For example, consider the elements of a typical SCPC channel unit for digital transmission, shown in Figure 6-1. This unit multiplexes and scrambles incoming data, provides convolutional coding for forward error correction (trading bandwidth for signal to noise ratio), modulates an assigned carrier and performs the inverse upon receiving, including carrier acquisition. All these blocks except for the MODEM are essentailly composed of digital logic and thus amenable to LSI. And in fact these elements are available today as LSI chips for specific limited applications. For example, a voice CODEC based on variable slope delta modulation, and convolutional coder/Viterbi docoder are examples of LSI chips currently advertised and available. Unfortunately, the most difficult and complex subsystem in Figure 6-1 is the MODEM itself which is composed mostly of analogue circuits, e.g., amplifiers, voltage controlled oscillators, multipliers, filters, crystal oscillators, etc., which are not readily amenable to LSI. Some manufacturers have attempted to develop hybrid units using digital logic and analogue amplifiers, but with limited success to date with respect to size reduction, testability, reproducibility and cost. Therefore, while it is possible that analogue circuits may be LSI'd by 1985, it appears that only the digital circuits (and there are a

goodly number in many of the service configurations) will be LSI's by 1985. A perusal of Volume 3, Appendix 1 (where interface equipment costs are broken down into considerable detail) will show the reader how the cost allocation with regard to LSI was performed in the study and the importance of LSI to particular configurations.

E. Miscellaneous.

It is worth mentioning that operations and maintenance costs are assumed to be minimal expenses to the annual service cost because all earth stations are assumed to be unattended but capable of servicing by locally available personnel. This means that outages due to failure and repair are longer than outages for earth stations with skilled technicians. However, a skilled technician costs an operating carrier approximately $30,000 a year including overhead and benefits. Thus, even the more complex earth stations such as for video teleconferencing are expected to be unattended but locally maintained. Part of the annual cost for O&M is a sum required to develop and maintain the skills of a local maintenance man. No uninterruptable power supplies (diesel generators and batteries), air-conditioning, exotic alarm and control or personnel facilities is assumed. Those rare locations requiring these items are associated with such a small number of terminals that these situations can be neglected as far as cost impact is concerned.

6.3 SATELLITE TECHNOLOGY

Beginning in 1962, with the launching of the Telestar and Relay and later Syncom experimental communications satellites, operational communication satellite technology evolved quickly, first via the Intelstat System, then by Canadian and U.S. Domsat Systems and finally by so-called Foreign Domestic Systems. Along with this evolution, NASA sponsored satellite and subsystem development programs such as the ATS series complemented the evolution and provided much technical support. Corresponding developments, particularly by NASA in launch vehicle technology was thorough and timely such that satellite operational capability was limited by traffic and not by launch vehicle technology. Today sophisticated satellites such as Intelsat IV, Intelsat V, the U.S. Domsats, and the Military "777", for example, are available to meet ever growing demands for more and better service.

Technical innovation is still going on at a rapid pace, however it is interesting to note that this innovation is mostly confined to communication hardware. More efficient TWTs, approaching 50% (expected to be near the practical limit), are available. Exotic but light weight filters and multiplexers composed of graphite composites and large deployable and/or multiple beam antennas are examples of industry efforts to improve communication satellites. Recently, GaAsFet amplifiers have been developed to the point where satellite use is possible; these amplifiers offer a substantial reduction in thermal noise compared to tunnel diodes, (from approximately 1100°K to 500°K at "C" Band) resulting in significant savings in earth station HPA costs. In addition, demands have required design and construction of larger and more complex satellites (Intelesat V, ATS 6 and Fleetsatcom) indicating industry competence in developing large complex satellites. Even larger launch vehicles are still available, if needed. Further, more efficient solar arrays both "blue" and "violet" cells are, in use increasing solar array efficiency by about 25%. These developments are significant and have been taken into account in the Study.

In addition to the above, the land mobile satellite capability can benefit substantially if a linearized Class B silicon bipolar transmitter can be developed so that "back-off" and intermodulation penalties can be avoided. Considerable success has been achieved to date using both "feed forward" and feedback methods over modest bandwidths. Without linearization a power loss up to 5db is encountered. Linearization techniques also apply to carrier type domsats. Frequently these transponders are operated in the linear region, e.g., in the "backed-off" multiple carrier mode and are power limited, not bandwidth limited. The resultant 5dB backoff, causes a 5dB reduction in capacity and presumably therefore a 5dB increase in transponder "cost". Consequently, there are applications for linearized amplifiers in both the potential land mobile service, and in the carrier systems. In the latter case the applications are 4GHz and 12GHz using primarily GaAsFet technology. It should be noted in passing that little success has been achieved to date in linearizing TWTs, basically because of the large bandwidth involved and the complex impedance functions caused by internal reflections.

For point-to-point communications multibeam satellites can focus more energy into the regions of interest, thus improving the communication efficiency and offering the possibility of frequency re-use through spatial separation of the beams. However, several problems arise in connection with this basic concept. It is desirable because of weight considerations to use only a single aperture to develop the multibeams using individual feeds. Both parabolic and spherical reflector antennas, front fed, Cassegrain, or offset fed have been considered and have been developed. Limitations occur due to sidelobes caused by limited focal region for feeds, blockage, feed coupling, etc., so that for many beams, single aperture-single beam arrangements are favored or resort is made to heavier more complex lens antennas. At high frequencies as high as say C-Band, the multiple antenna solution is reasonable if only modest beamwidths, say 4^{o} are desired. Another substantial problem is the signal routing problem within satellites. When only a single wide coverage antenna is used as in the present U.S. domsats, all the satellite transponders are available to users within the single coverage area. When multiple beams are used, signals arriving at the satellite must be directed to the correct downlink spot beam. For complete access using FDMA, and a satellite with "b" discrete beams, at least b^2 routing filters are required; for this minimum the transmitters driving the downlink beams are operated in the multiple carrier mode, normally requiring a 5db-6db backoff. The combination of the filter weight and power penalty reduces the attractiveness of this concept. Use of $2b^2$ filters and b^2 output amplifiers avoids multi-carrier operations, but results in a heavy satellite. These limitations can be overcome by the use of a version of satellite-switched TDMA, described in Appendix 6 in which an onboard switch matrix switches received TDMA signal bursts to the proper downlink beam. The "destination" filters are thus avoided and the transmitters only amplify one carrier at a time and so avoid the use of "backoff". The satellite switch composed of an "m x n" array of high frequency switches (using PIN diodes for example) is similar to a crossbar telecommunication switch, controlled by a small computer and updated by the satellite command system. The satellite switch is state of the art. The disadvantage of such a system is the costly TDMA equipment in the earth stations and the high aggregate bit rate per station. Provision of network control, redundancy, synchronization, fail soft, demand assignment, etc. relating to the TDMA approach have not been developed because of the expense and market uncertainties.

Dual polarization is in use in Intelsat, Comstar and Satcom to increase capacity by providing polarization isolation to co-channel bands. These techniques primarily benefit high capacity carrier systems. Isolation is limited by the antenna technology and by depolarization due to rain. The systems considered in this study did not consider use of dual polarization directly except for the land mobile case.

Similarly, components offering substantial increases in satellite payload such as cesium or mercury bombardment ion engines, with high specific impulse have been developed and flight tested as experiments. Such devices offer promise of reducing the approximately 15% of the satellite payload allocated for hydrazine fuel, making most of this available for extra communications. Similarly, fuel cells in various forms offering substantial reductions in the weight of energy storage systems are being developed.

The transition from experimental or conceptual status for SS-TDMA, fuel cells and ion engines is inhibited by a lack of orbital demonstration programs. Commercial carriers and other satellite owners, faced with the prospect of untried technology do not accept the risks and opt for the "tried and true", established technology. This trend is increasingly prominent in latter years since the decline of government-sponsored R&D in communications satellites; ATS-6 and CTS being the last of the demonstration satellites. Consequently, for the purposes of this study it has been assumed that this status quo will continue and that these valuable technologies will not be applied to operational communications satellites in the near future. Recognizing the long gestation period for satellite systems, the cutoff for 1985 technology is 1980 to 1981. There are apparently no existing plans to demonstrate these technologies by 1981 except for a limited SS-TDMA system being implemented on TDRSS.

The Space Shuttle is one final technical innovation having a bearing on the study results. The more obvious cost benefits such as lower launch cost and lower insurance cost (man-rated reliability and Shuttle return-to-earth if the mission aborts) have already benefited the study results. A larger available spacecraft volume reducing the cost of deployable elements also can have a bearing on space segment costs. Many of the configurations discussed herein can benefit from the larger shroud volume. The cost savings, however, are not expected to be dramatic and there is every indication presently that satellite designers will not radically change spacecraft design or test procedures or change piece-part quality. Such radical changes will likely only occur with the advent of on-orbit repair or return-from-orbit capability forecast in the future for Shuttle operations.

However, present Shuttle operational plans call for weekly launches of modularized payloads, a large step forward in launch turn-around time as contrasted with the 60 days currently required if a launch vehicle is available at the launch site and six months to a year if one is not. It is believed that such short turn-around times, particularly if warranted by emergency conditions, might encourage the use of single spacecraft in orbit for operational systems, with backup provided by a ground spare. Some added redundancy would be necessary - for example, the satellite operator may be reassured if completely redundant and independent propulsion, attitude control and power electronics are provided even if the satellite communication performance is somewhat reduced. In the event of a disastrous on-orbit failure - or for more likely a threathened failure

- a backup satellite can be rushed into orbit with an accelerated Shuttle launch schedule. The operating risks of single in-orbit satellites have already been accepted by satellite carriers for extensive periods of time so the procedure is not necessarily new. The payoff can be estimated by considering a specific example. The Shuttle launched - Atlas/ Centaur type space segment annual cost used in this study is $26. 1M per annum including cost of two on-orbit satellite, two launch vehicles, one ground backup satellite and other sundry costs listed in Volume 3 Appendix 2, Satellite Characteristics, Table 2-18. Eliminating the second on-orbit satellite and its launch and related costs reduces the annual cost from $26. 1 M to $17. 1M, a cost reduction of 35%. While this estimate is idealized to some extent, (the single satellite will require additional equipment), it is clear that substantial savings are possible from this operational mode. This operating mode was not considered for the purpose of this study because neither the Government or industry currently have plans to operate systems in this manner. The savings are more dramatic than improving propulsion or energy storage efficiency.

6.4 SYSTEM TECHNOLOGY

Aside from satellite and earth station technology considerations there are system concepts which can benefit performance and cost. Many of these have been used in the study to indicate benefits and costs. An important consideration is satellite multiple access or method for routing signals through to their destinations. For most of the systems considered herein the satellite access is rudimentary since the satellite has only one or four beams. Even so, both FDMA and TDMA is considered in the important audio/ fax teleconferencing case as an example. Single channel per carrier (SCPC) is another access method, essentially a version of FDMA, which permits access to users sharing a transponder and within a view of a common antenna beam access has been discussed above in relation to satellite technology. A novel approach to access, not considered herein, coded with an address is packet switching, exemplified by the ALOHA system in which candom data bursts are transmitted through the same satellite facility. The destination recognizes only its coded address. Communications is such a system can be blocked, and the average efficiency of the transmission system is low. Nevertheless, there are applications for such systems.

In setting up the service models various modulation, coding and detection schemes are considered. While there may be, for each particular service an optimum arrangement, this optimization is beyond the scope of the study. Alternately, modulation, coding and detection schemes assumed are essentially based on experience and tradition with regard to the different services. For example, radio broadcasting modulation is assumed to be FM with threshold extension. Multiplexed data and voice is assumed to be digital (4 Ø PSK, convolutional coded with Viterbi detection). The reasons for these selections are discussed in Volume 2 Section 2 for individual services. It is clear that considerable development is ongoing with digital communications and consequently digital modulation, coding and detection development is active. LSI is aiding

this development because LSI favors digital logic performance and cost. LSI is causing a revolution in digital system application and it is believed will finally result in clear cut preferences for digital techniques over analogure techniques in the future. The intense activity today in signal processing, modulation and detection is sponsored by government (primarily military) and by commerical interests. Much of this work is used as background in selecting suitable, ostensibly attractive, communications parameters for the study services.

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